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(12) **United States Patent**
Nguyen et al.

(10) **Patent No.: US 9,078,763 B2**
(45) **Date of Patent: Jul. 14, 2015**

(54) **MULTI-LOBE ARTIFICIAL SPINE JOINT**

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(73) Assignee: **DIMICRON, INC**, Orem, UT (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/099,945**

(22) Filed: **Dec. 7, 2013**

(65) **Prior Publication Data**

US 2014/0172100 A1 Jun. 19, 2014

Related U.S. Application Data

(63) Continuation of application No. 13/445,833, filed on Apr. 12, 2012, now Pat. No. 8,603,169, which is a continuation of application No. 12/028,740, filed on Feb. 8, 2008, now Pat. No. 8,163,023.

(60) Provisional application No. 60/889,217, filed on Feb. 9, 2007, provisional application No. 60/914,469, filed on Apr. 27, 2007.

(51) **Int. Cl.**
A61F 2/44 (2006.01)
A61F 2/30 (2006.01)

(52) **U.S. Cl.**
CPC ***A61F 2/4425*** (2013.01); *A61F 2/30742* (2013.01); *A61F 2002/302* (2013.01); *A61F 2002/30138* (2013.01); *A61F 2002/30158* (2013.01); *A61F 2002/30365* (2013.01); *A61F 2002/30369* (2013.01); *A61F 2002/30934* (2013.01); *A61F 2002/443* (2013.01); *A61F 2002/444* (2013.01); *A61F 2002/449* (2013.01); *A61F 2220/0033* (2013.01); *A61F 2230/0017* (2013.01); *A61F 2230/0026* (2013.01); *A61F 2230/0065* (2013.01)

(58) **Field of Classification Search**
CPC A61B 2/44; A61B 2/4425
USPC 623/17.14, 17.15
See application file for complete search history.

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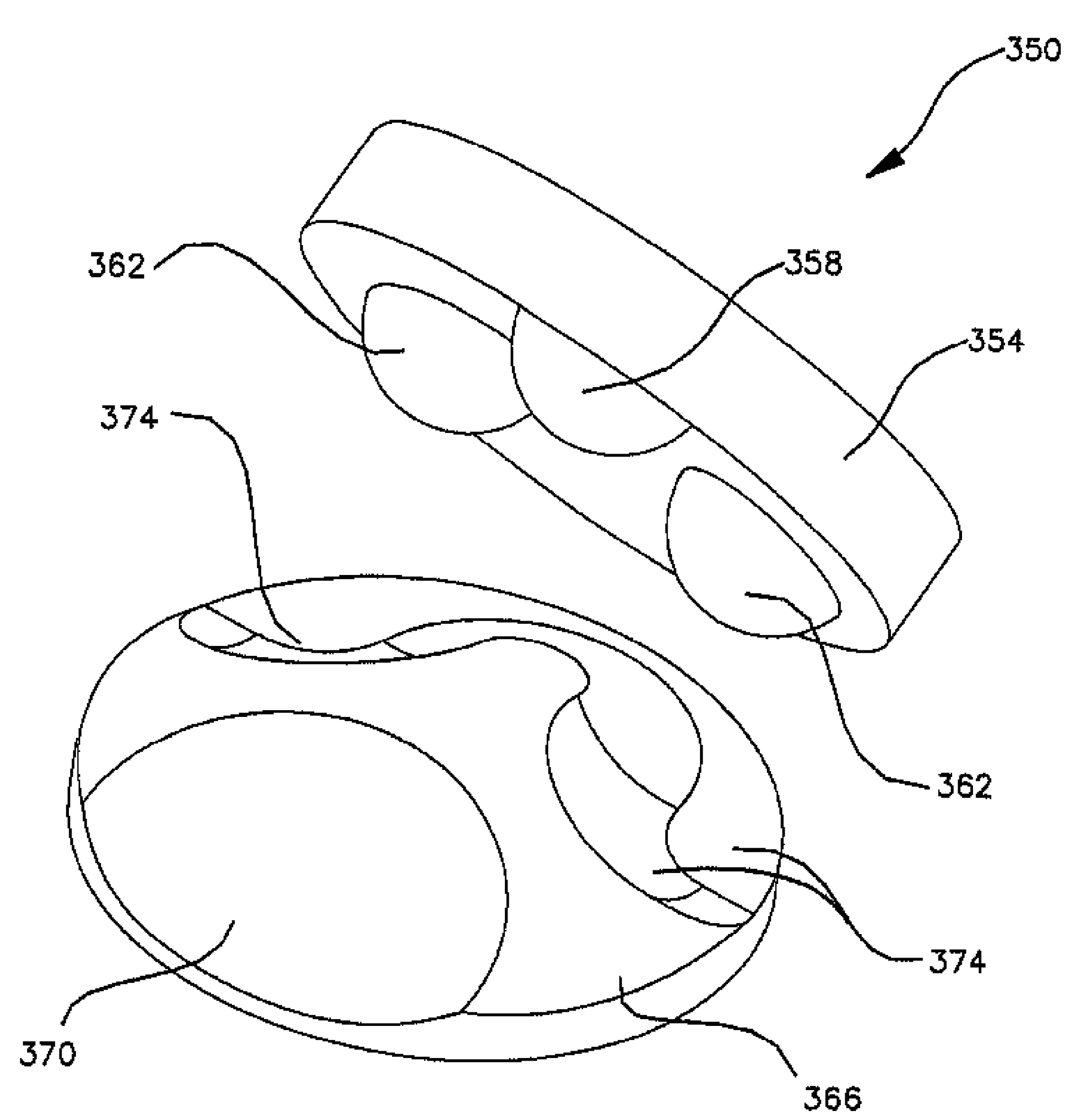
Primary Examiner — Andrew Yang

(74) *Attorney, Agent, or Firm* — Pate Peterson PLLC; Brett Peterson

(57) **ABSTRACT**

An artificial disc is provided which more closely matches the movement of the natural spine. The artificial disc uses one or more projections and corresponding recesses to provide a sliding articulation. The artificial joint is inherently stable in that compressive forces placed on the disc such as the weight placed upon the joint or the tension of surrounding tissues urges the joint towards a neutral position and not farther away from a neutral position.

29 Claims, 42 Drawing Sheets



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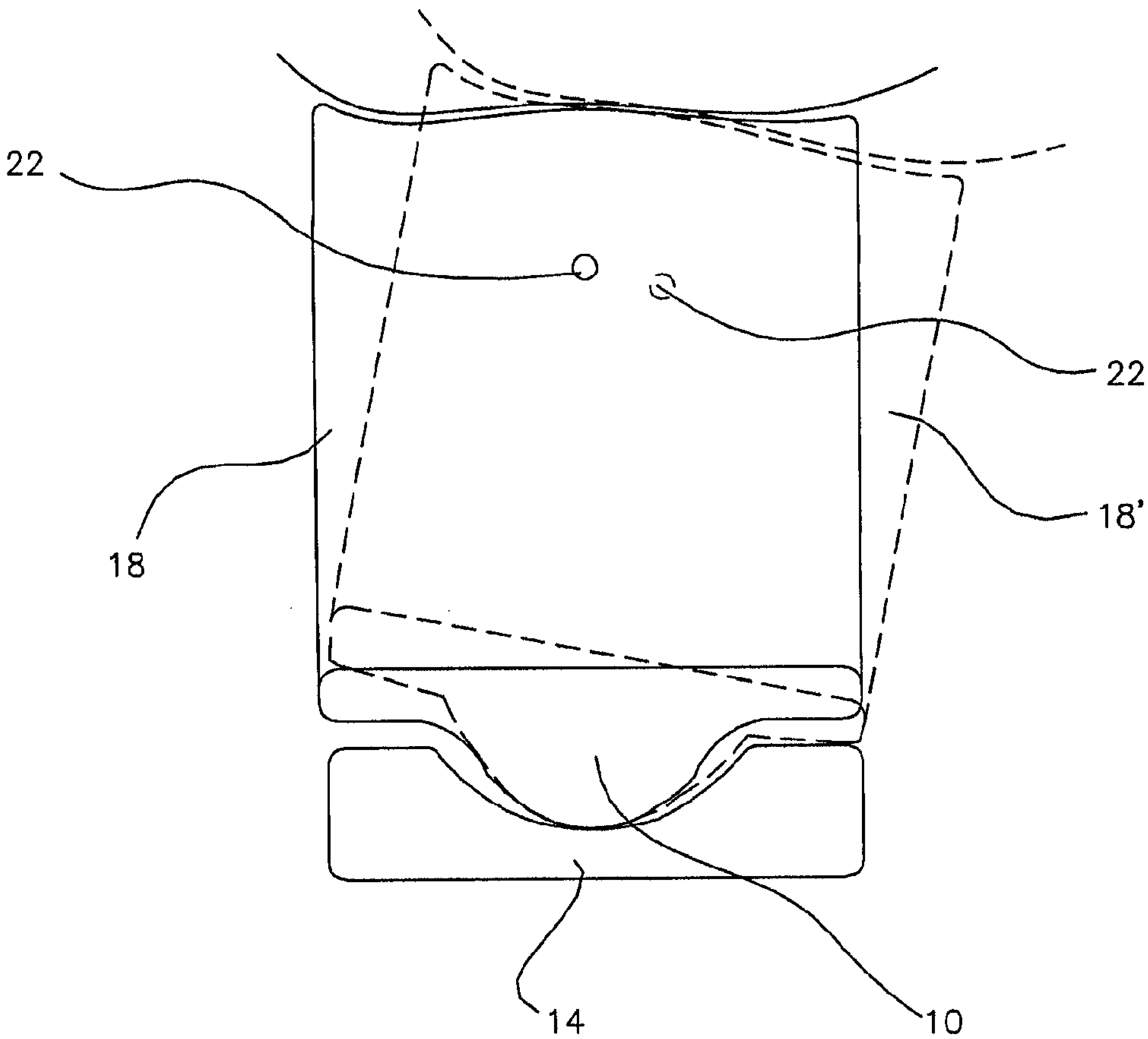

FIG. 1
(Prior Art)

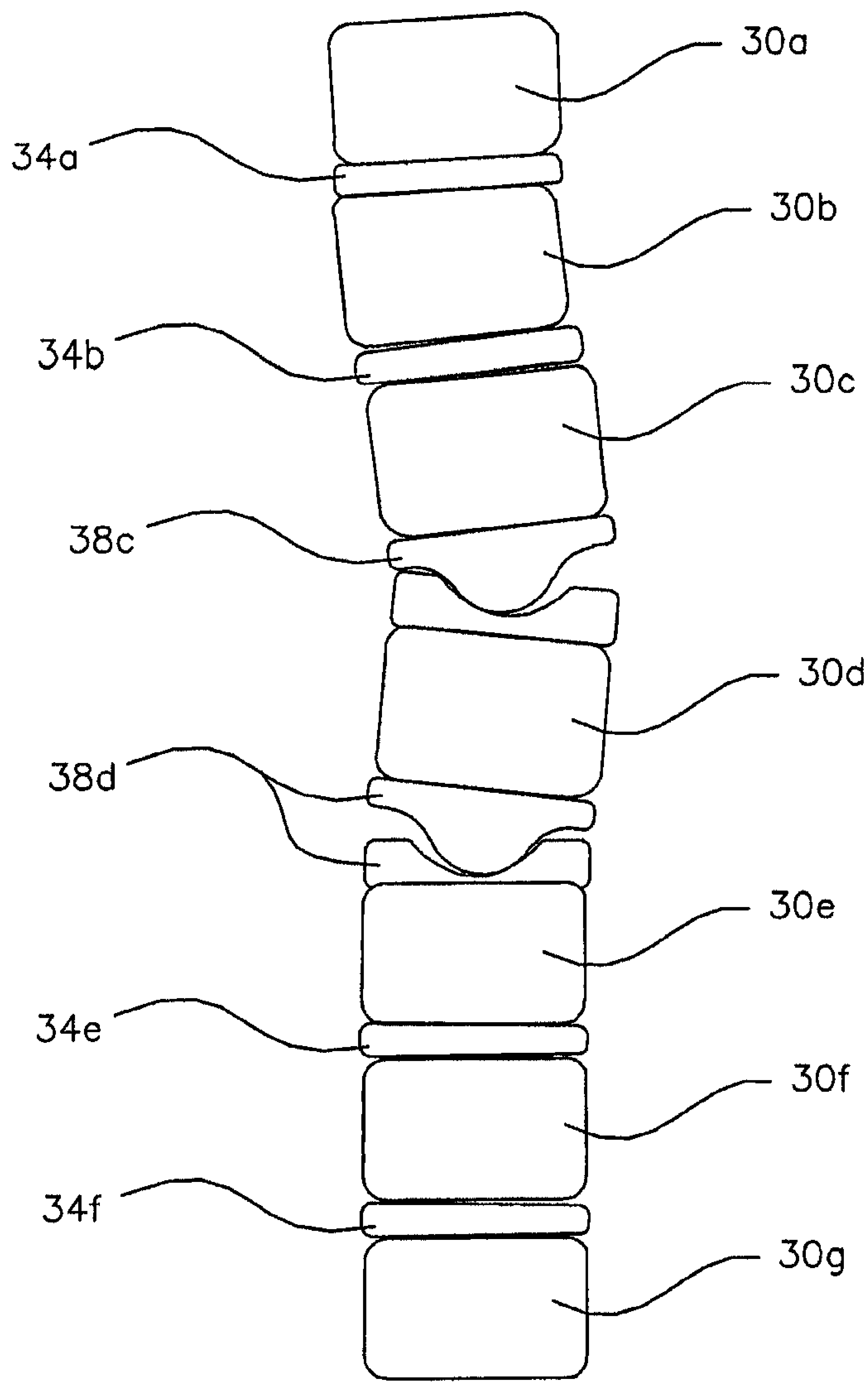

FIG. 2
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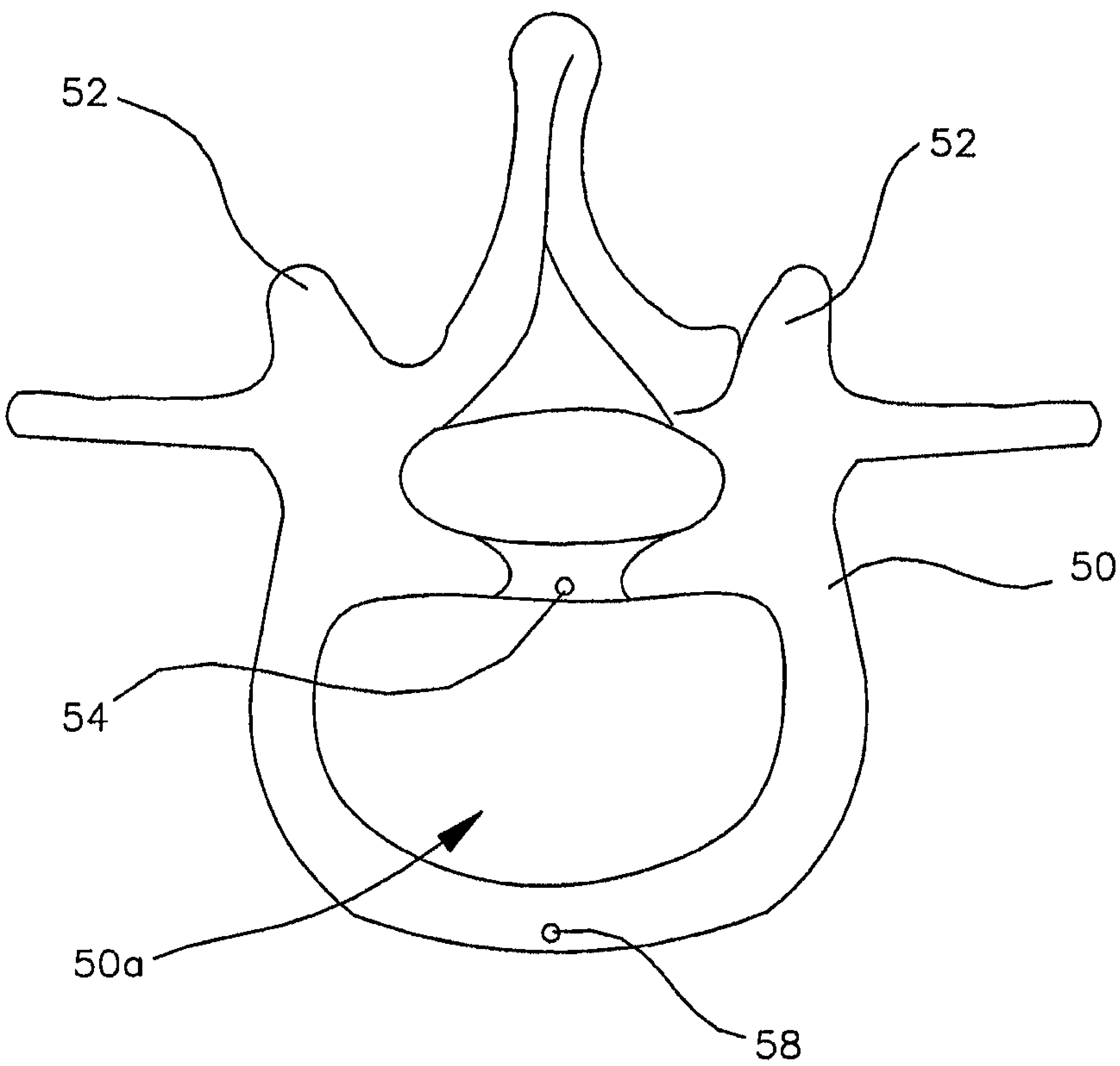

FIG. 3

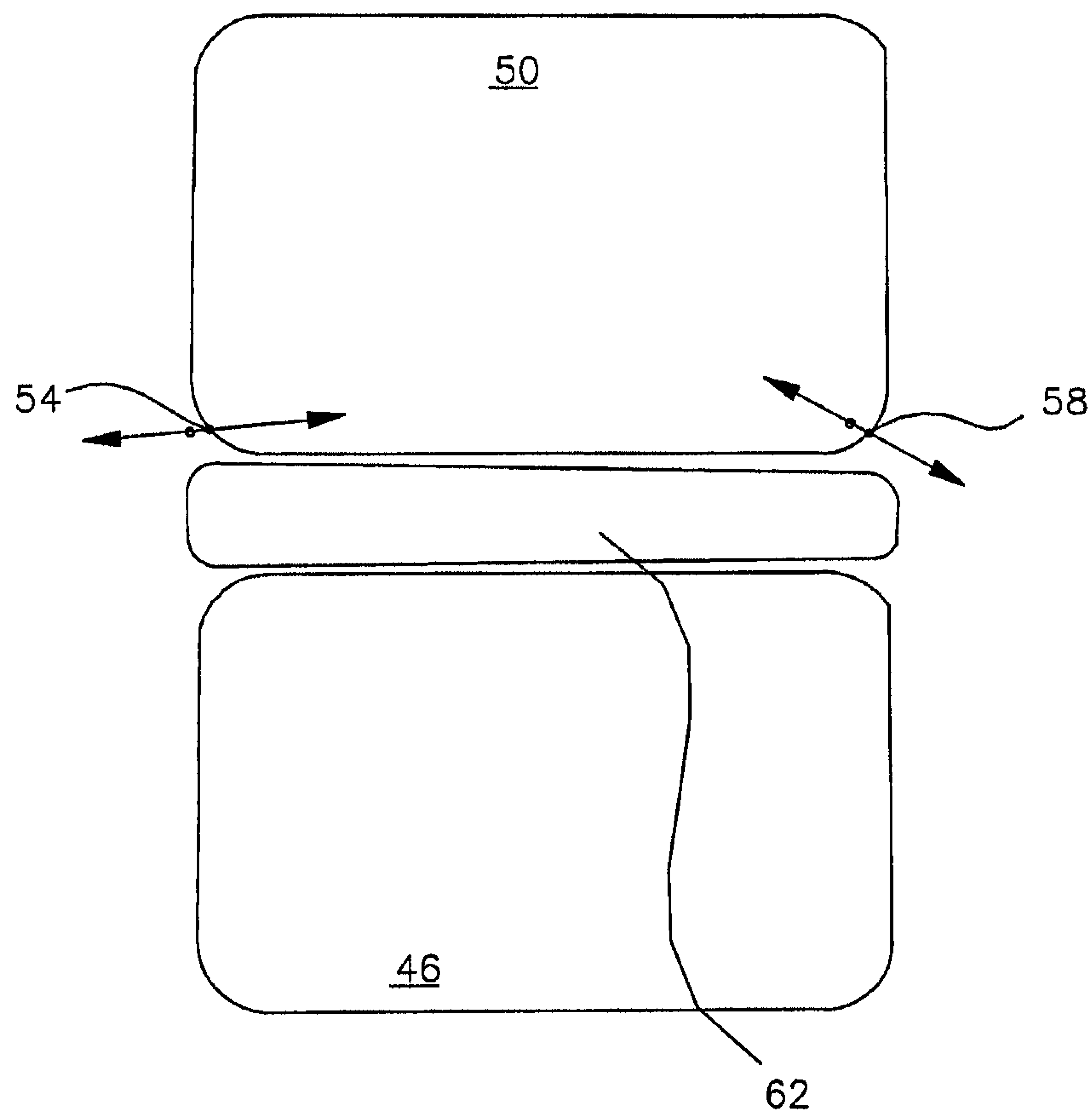

FIG. 4

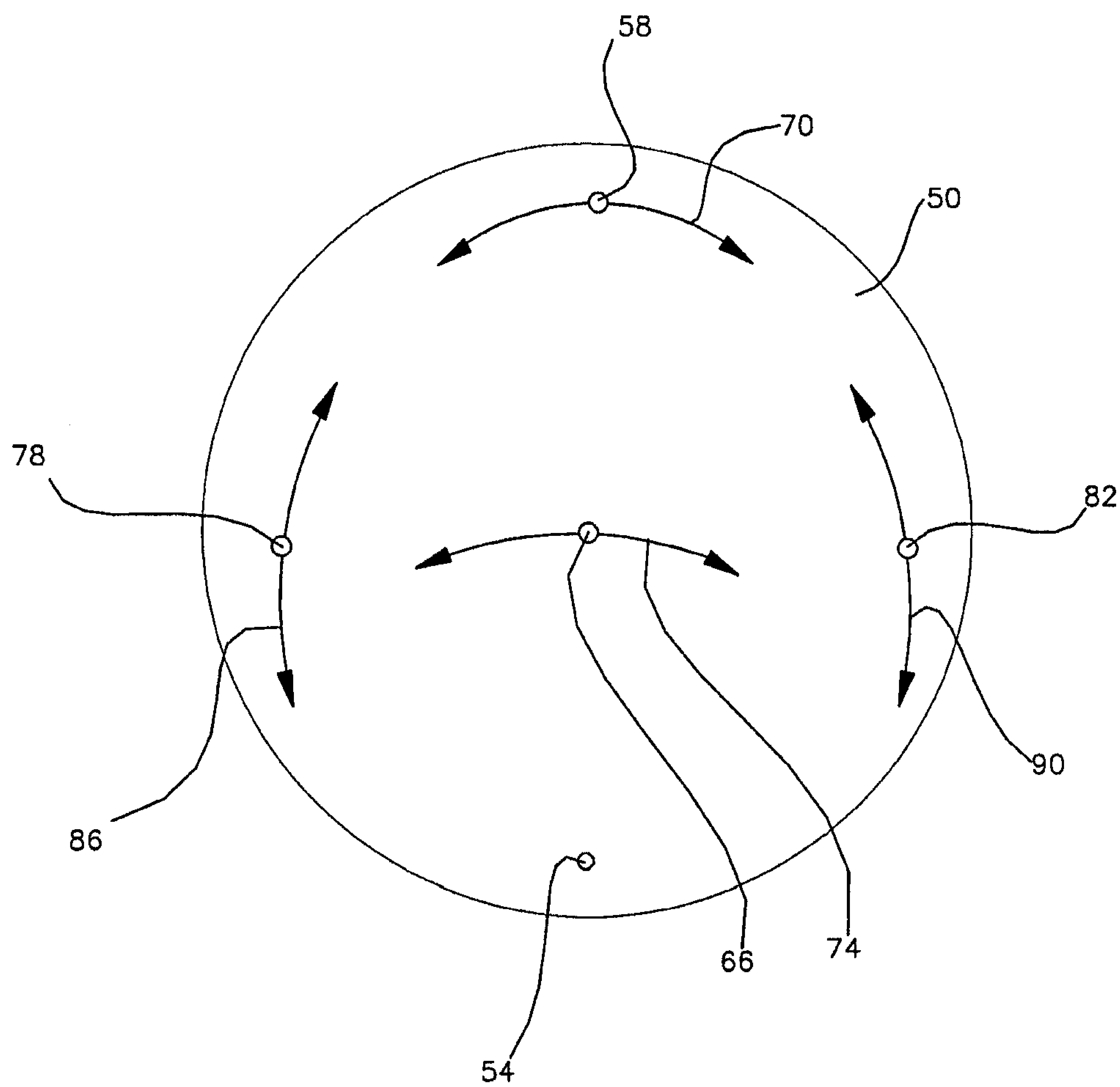

FIG. 5A

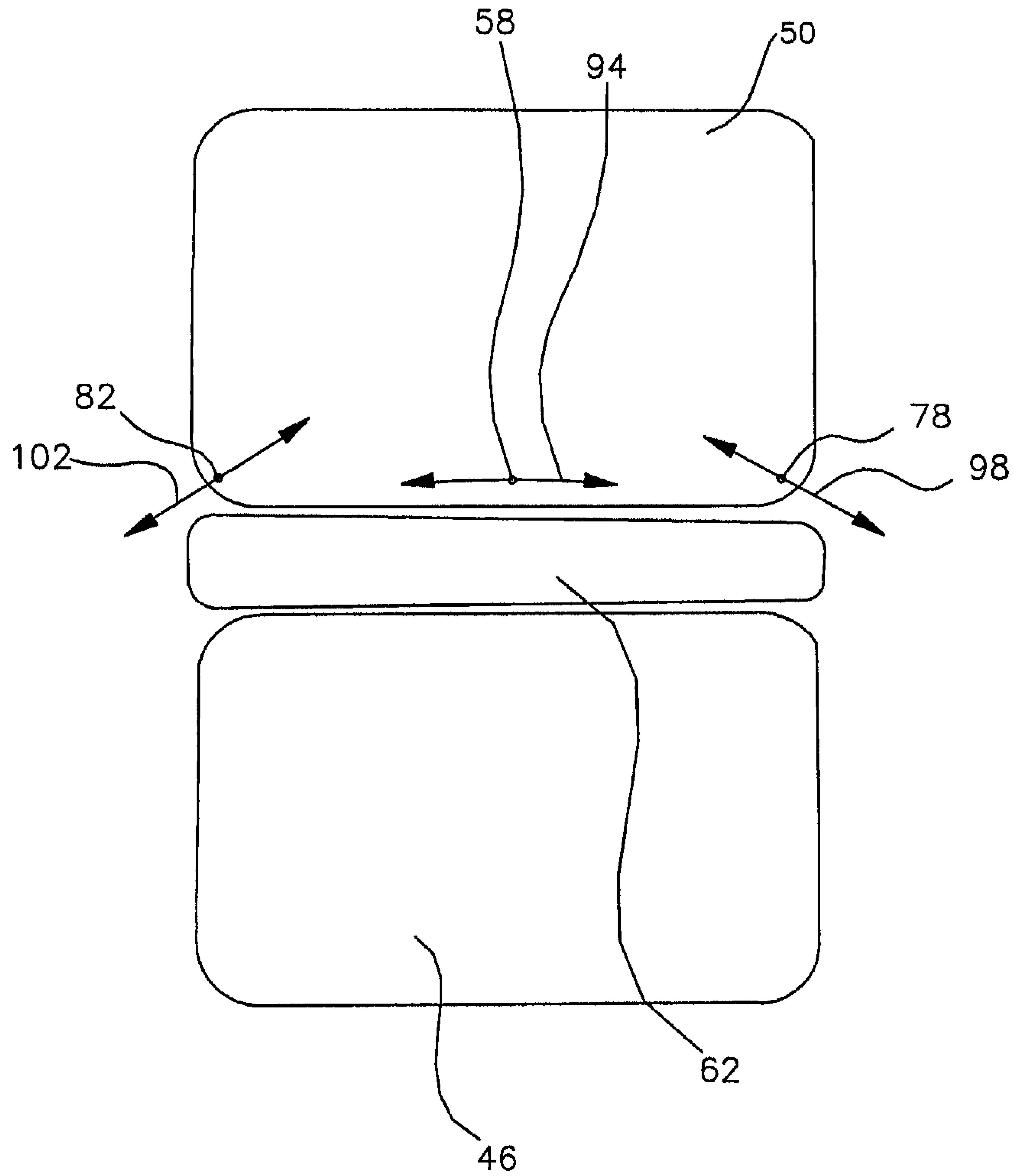

FIG. 5B

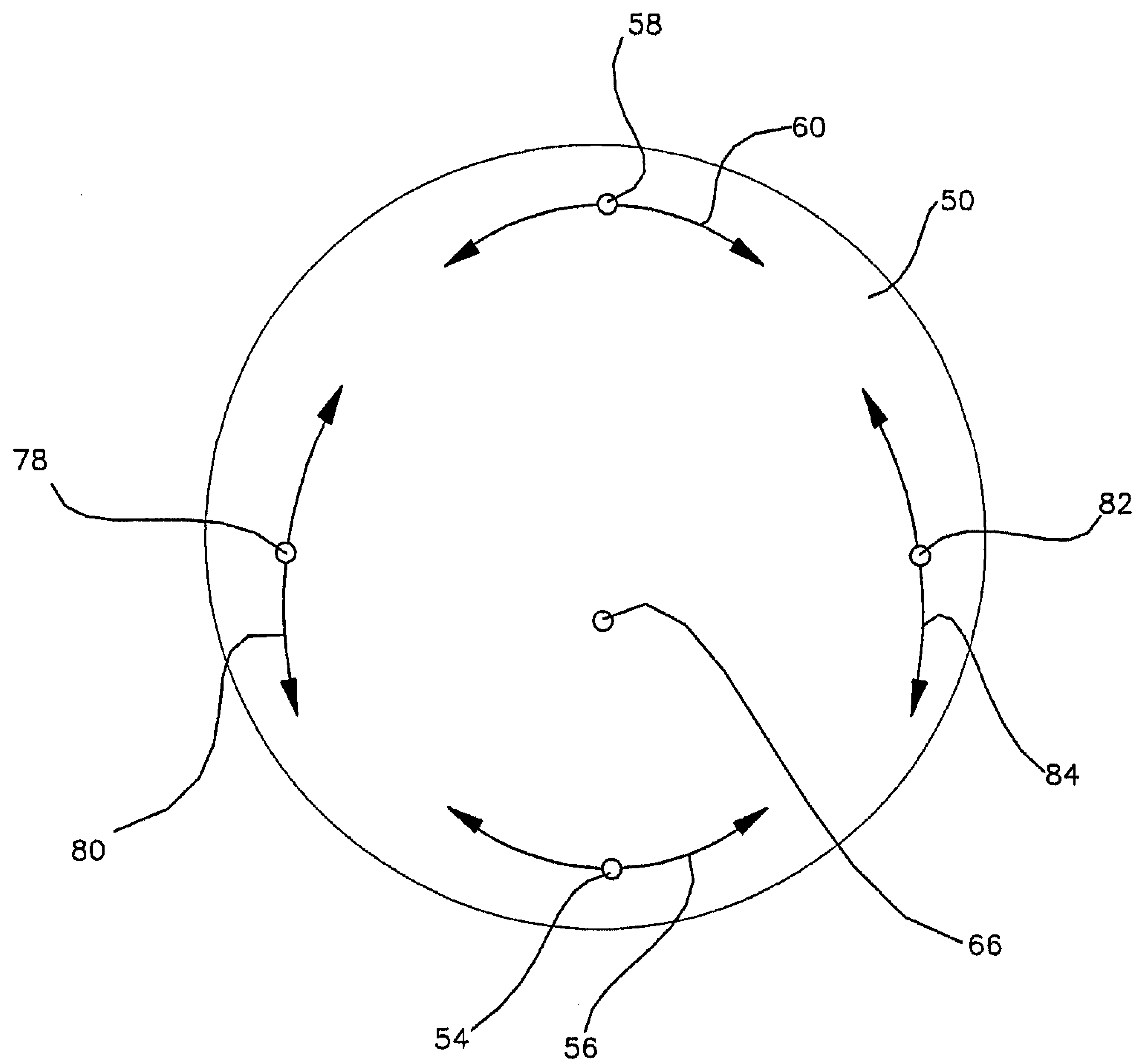

FIG. 6A

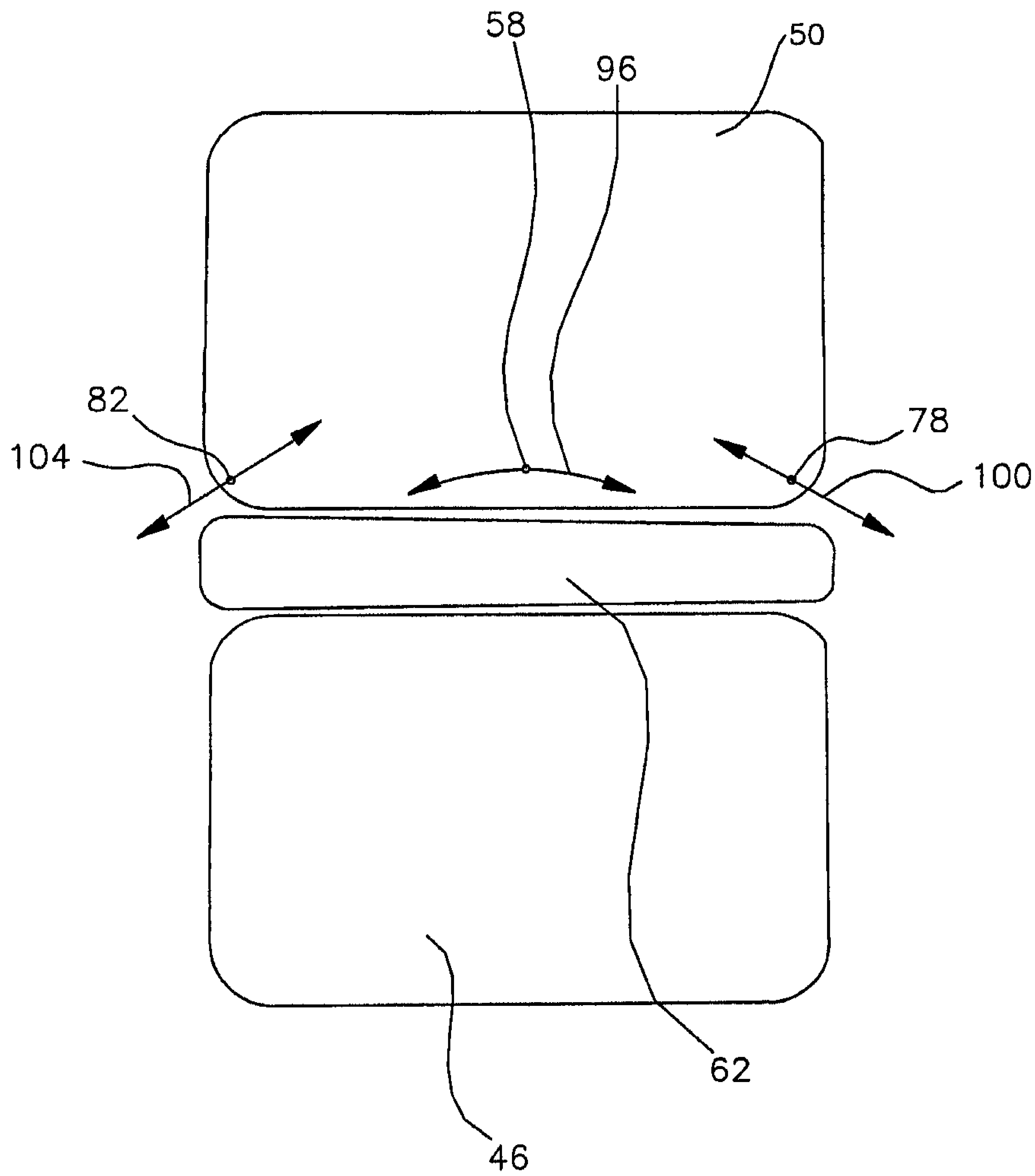

FIG. 6B

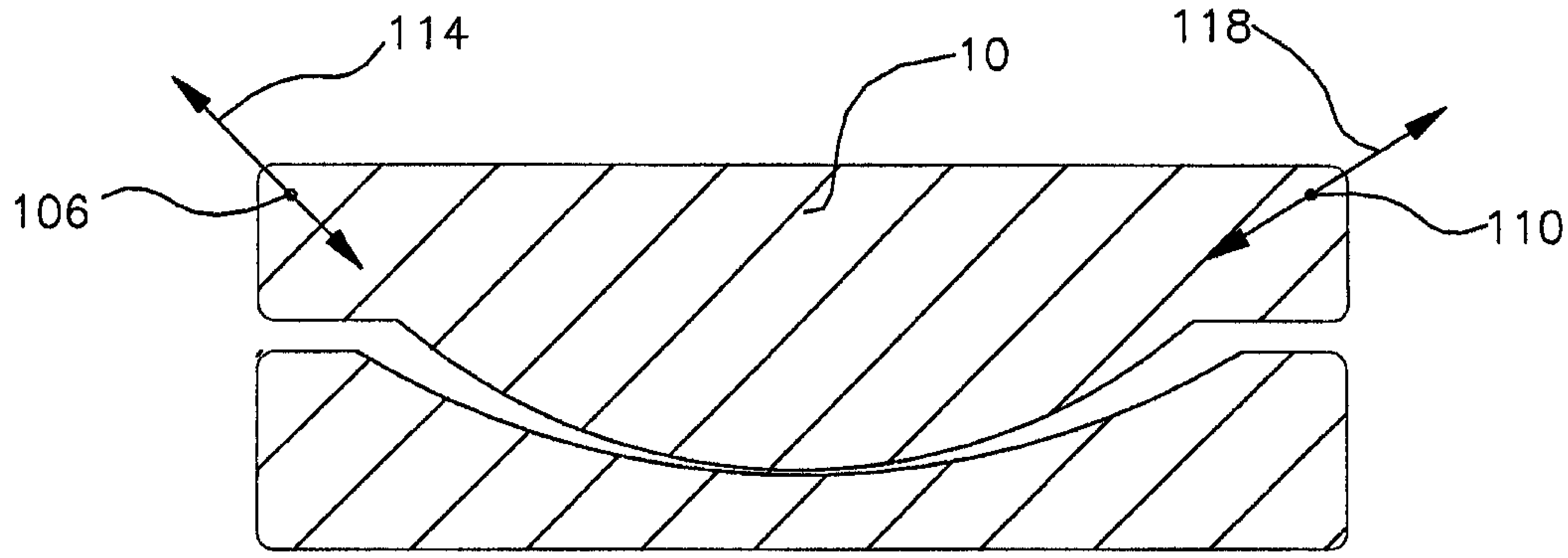

FIG. 7A
(Prior Art)

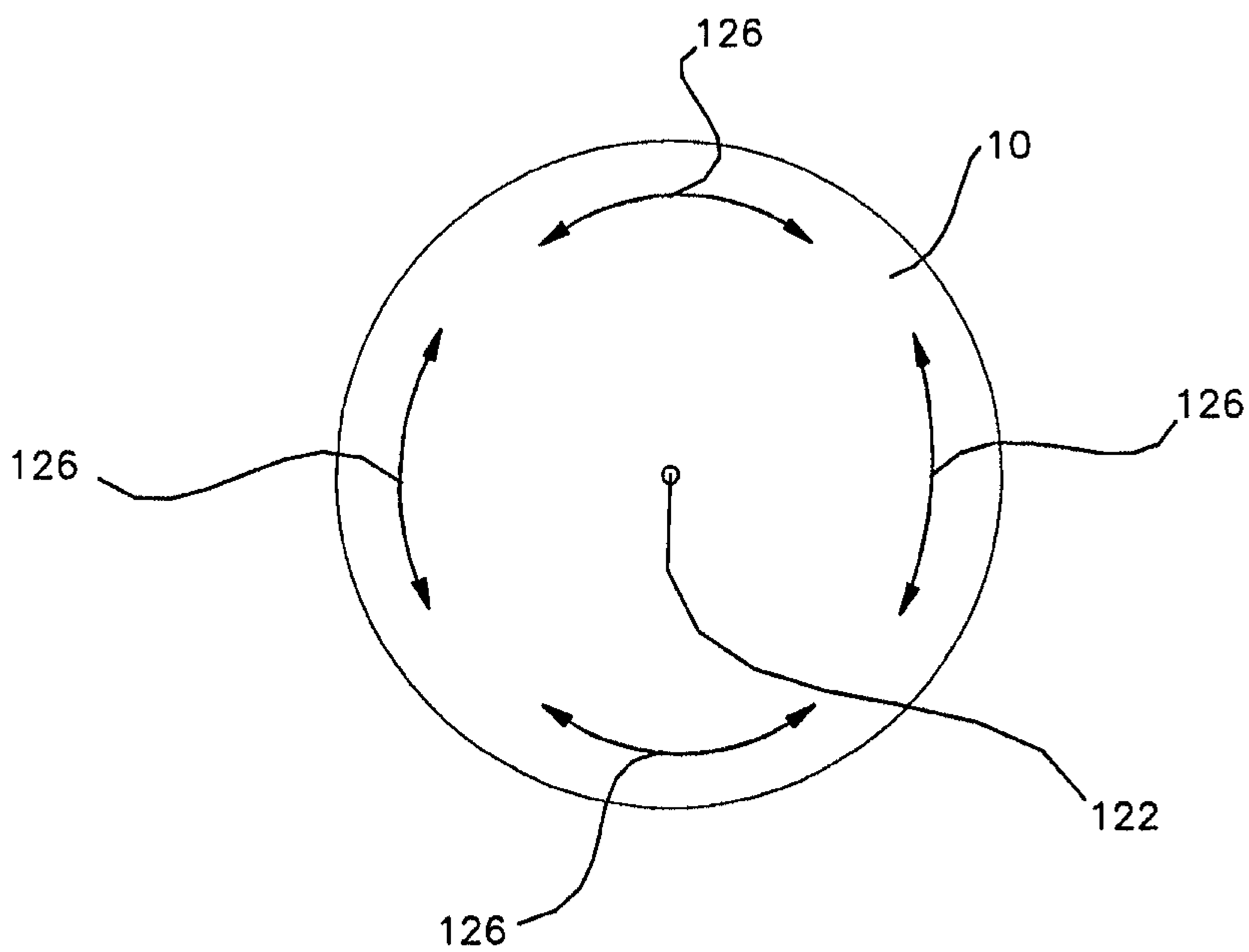

FIG. 7B
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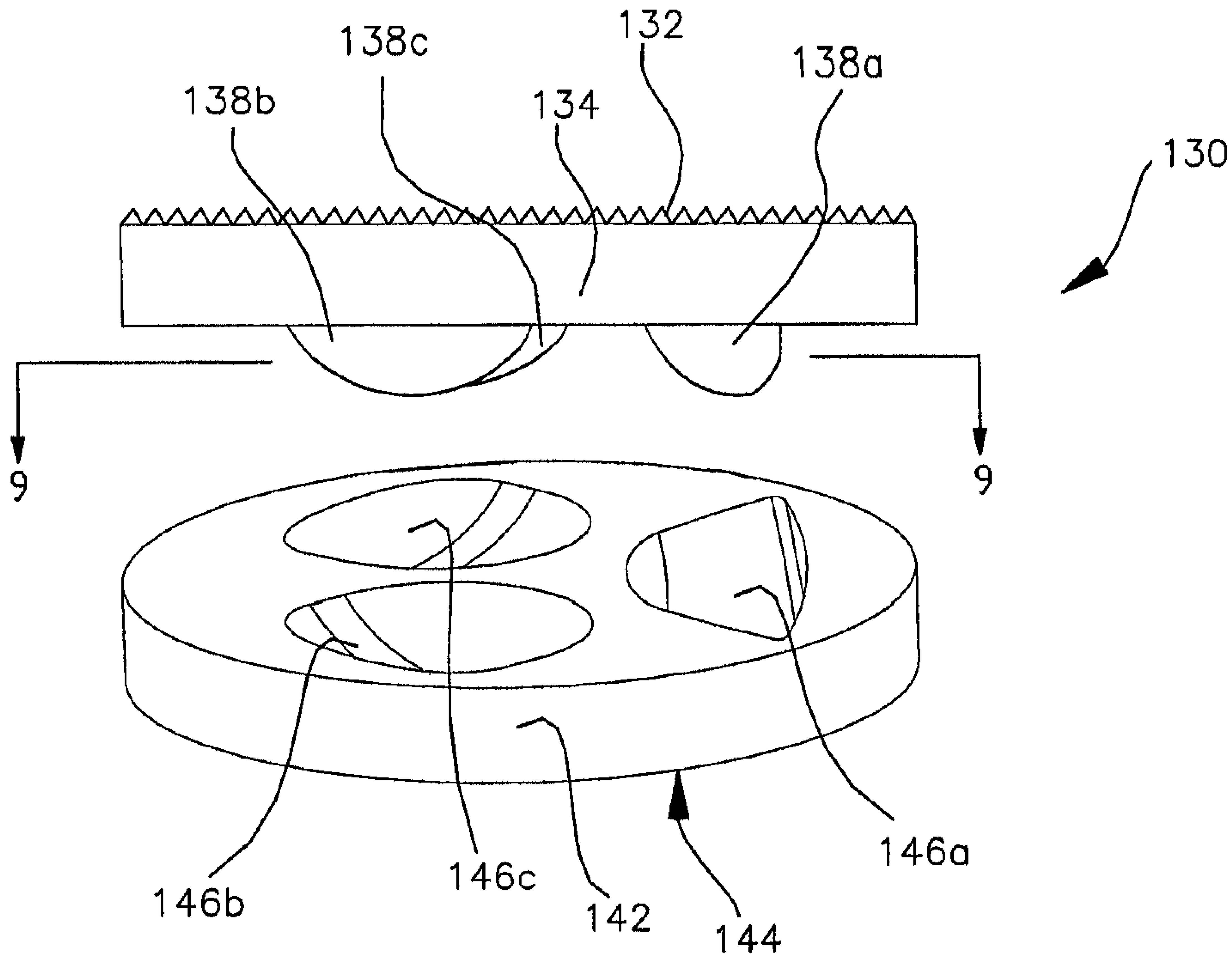

FIG. 8

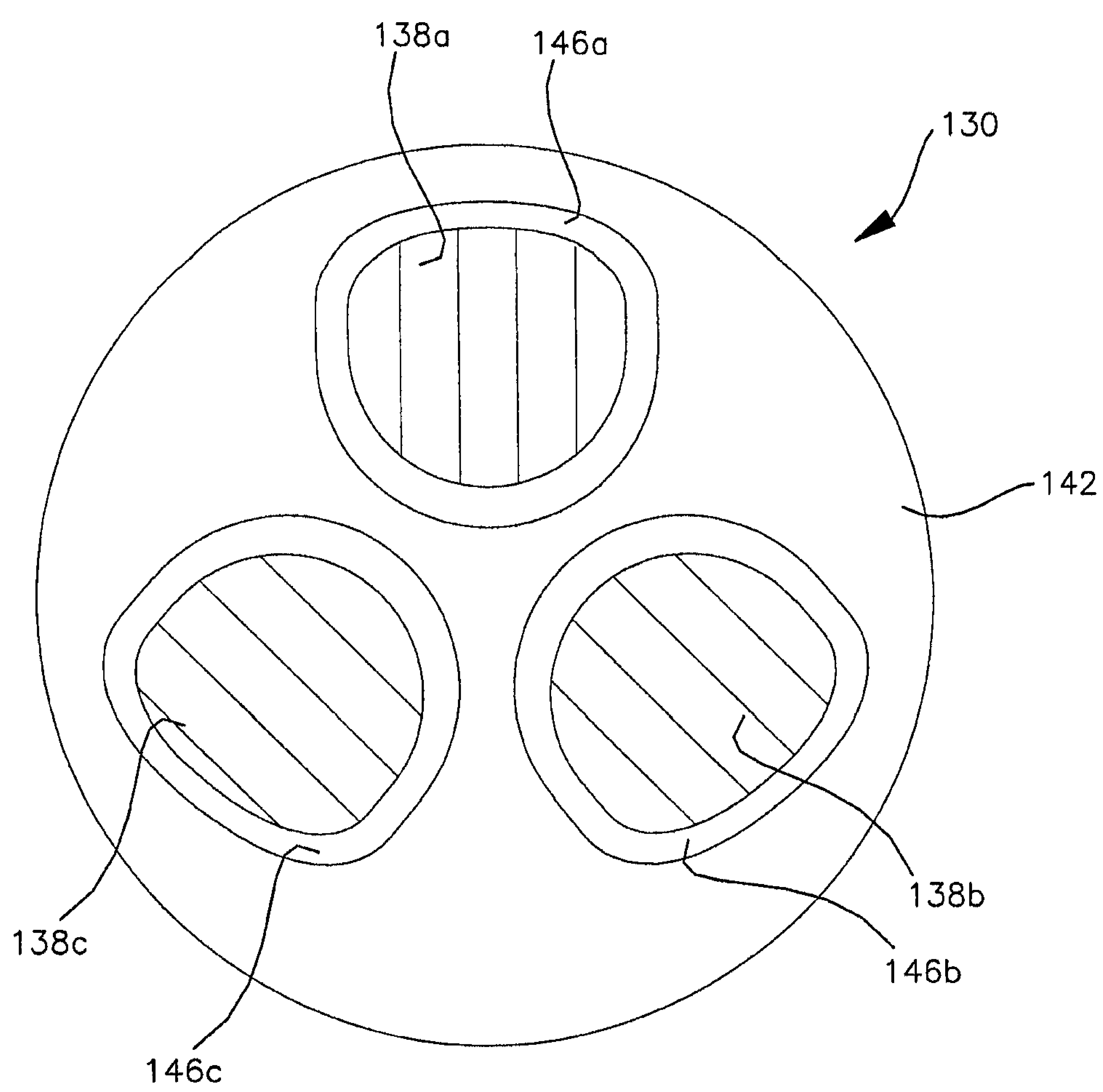

FIG. 9

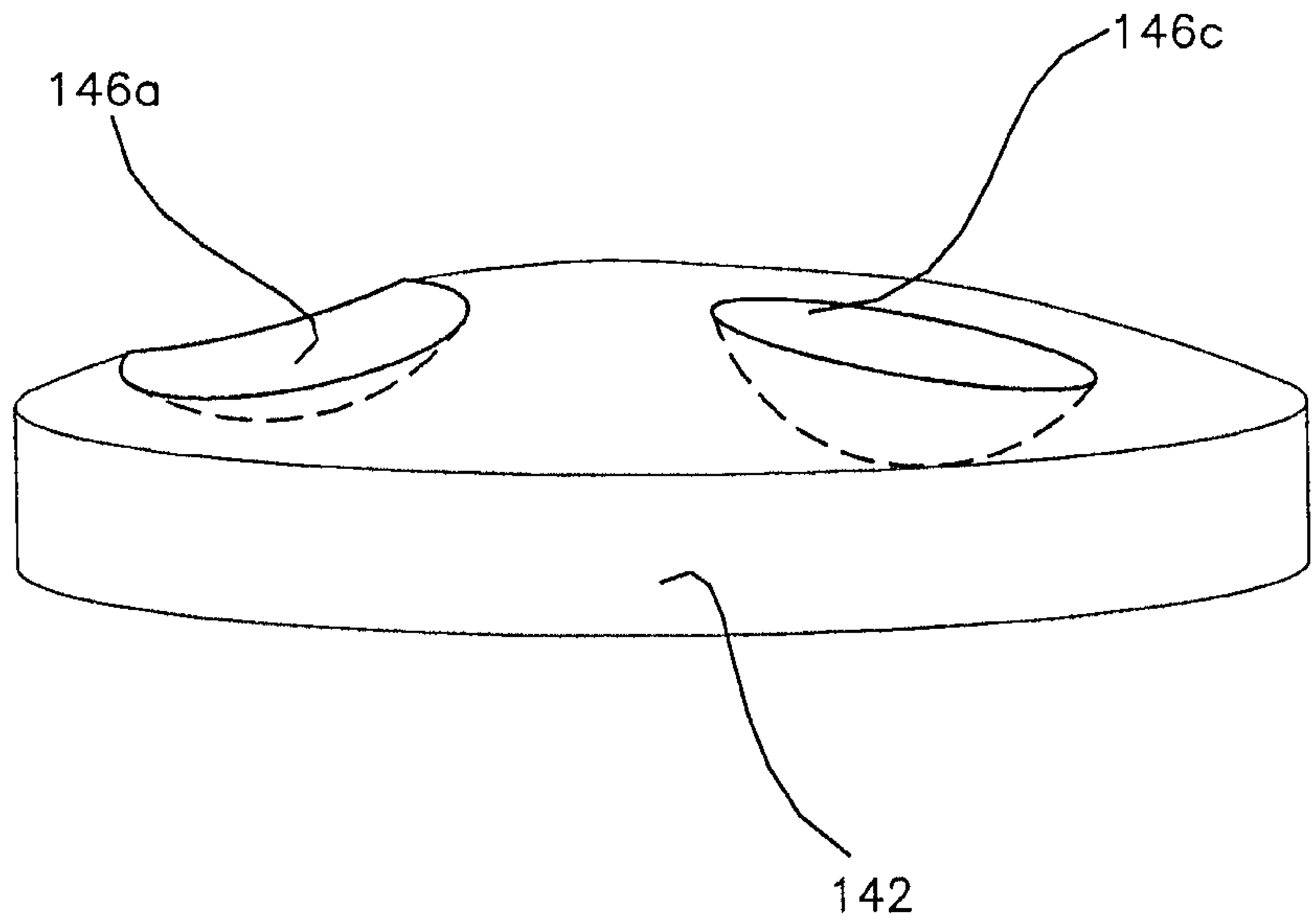

FIG. 10

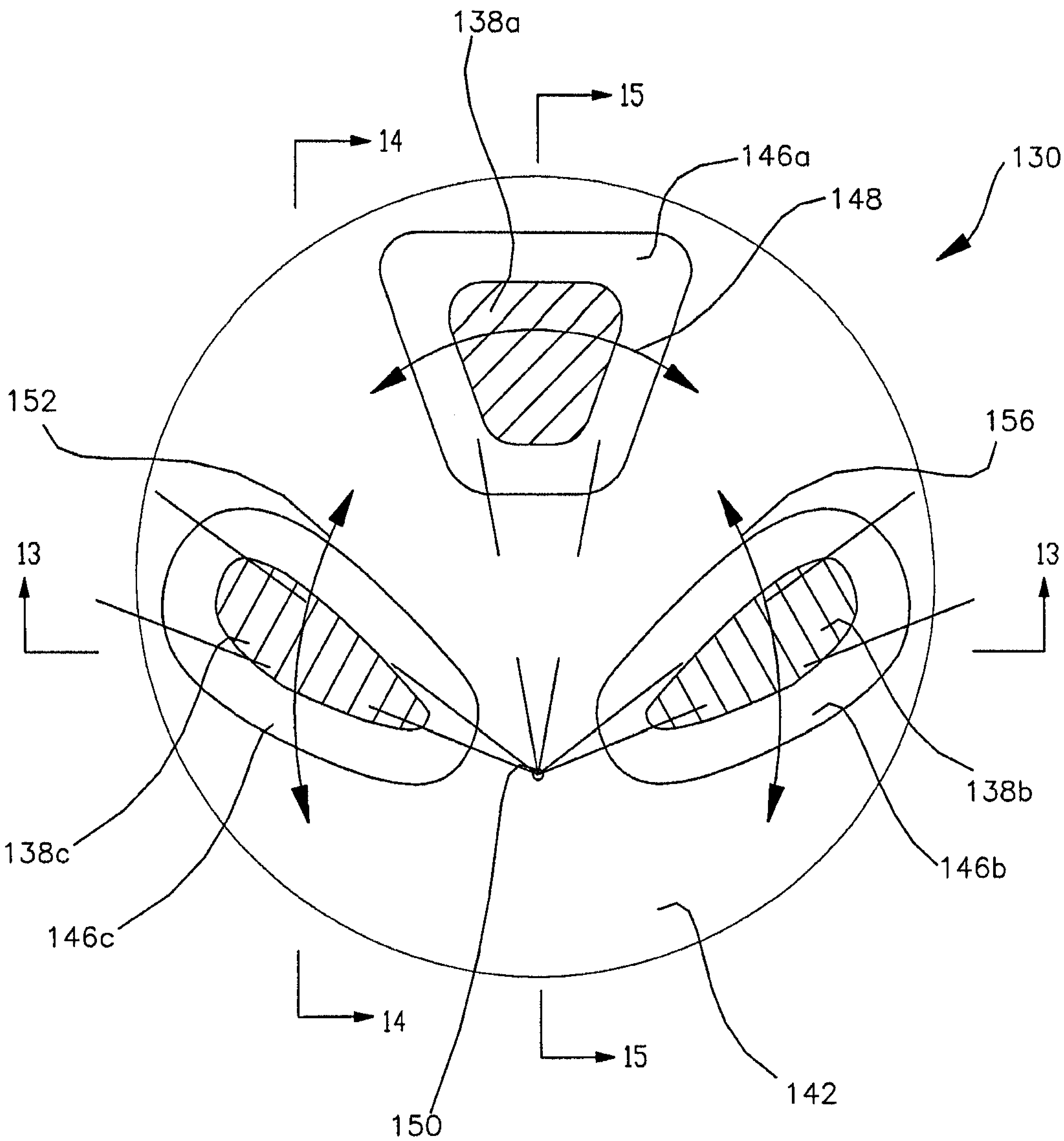
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FIG. 11

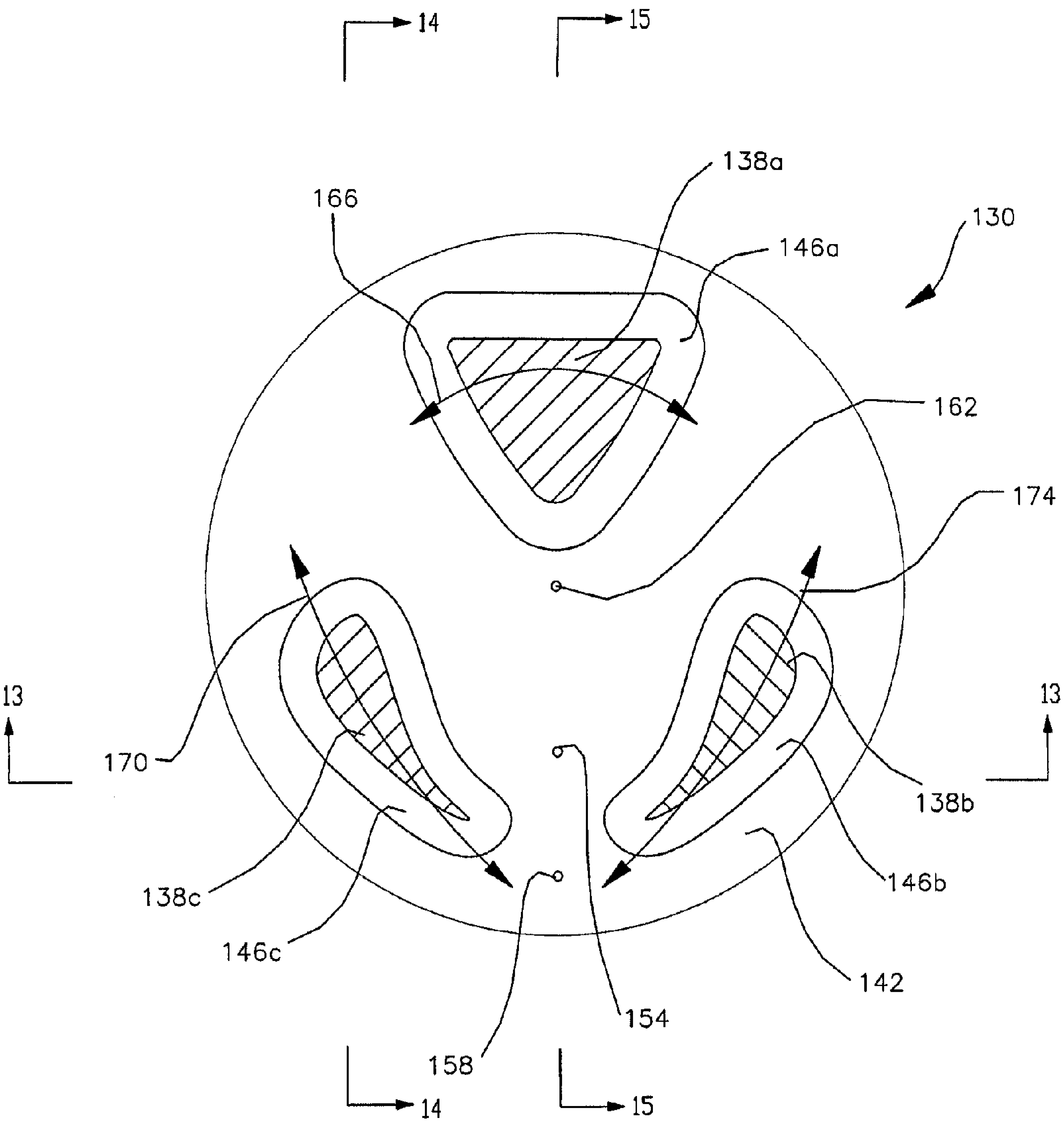
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FIG. 12

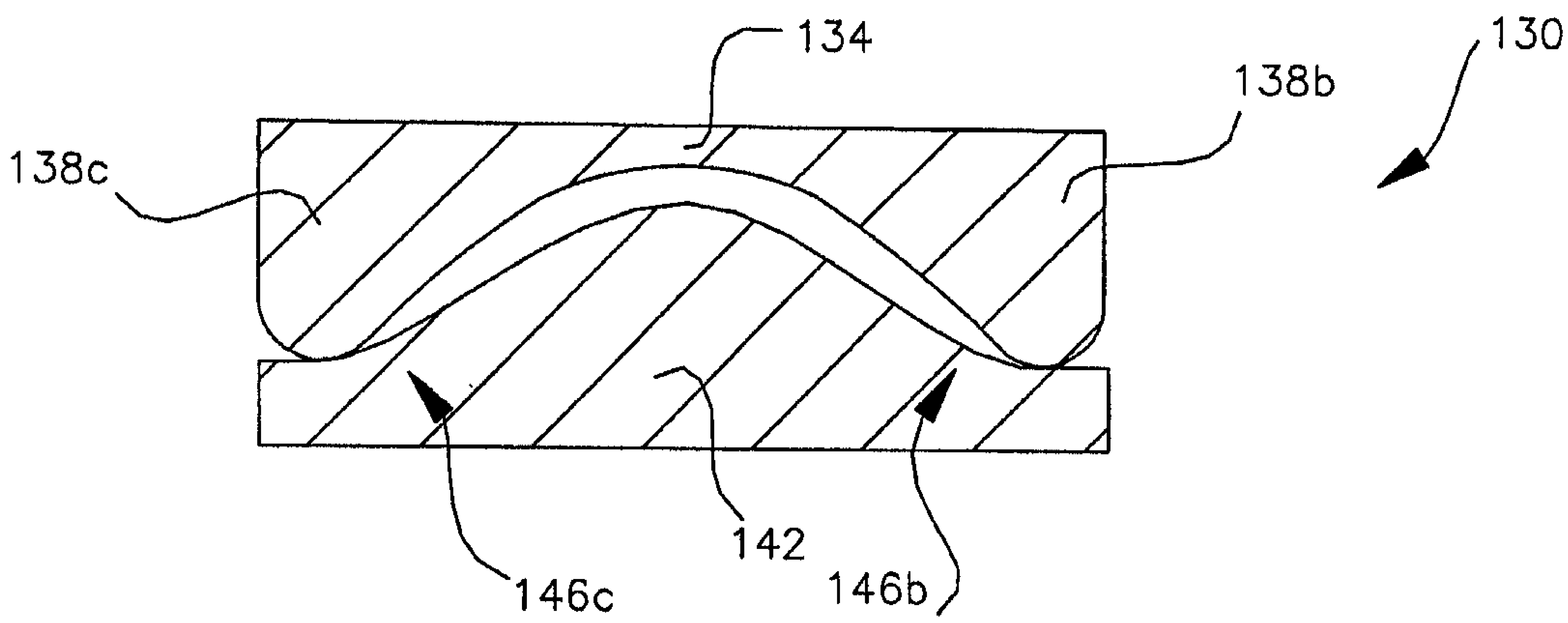


FIG. 13A

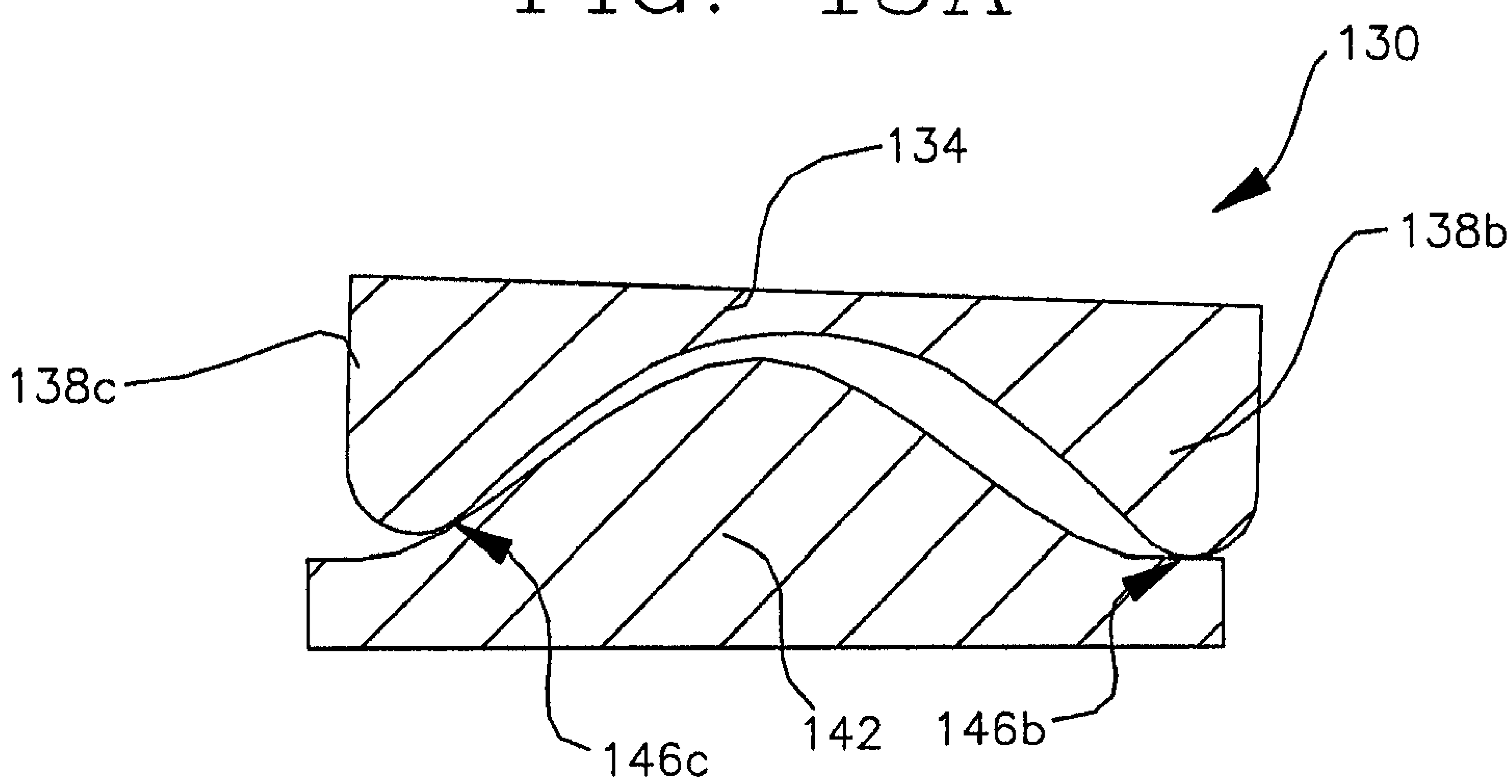


FIG. 13B

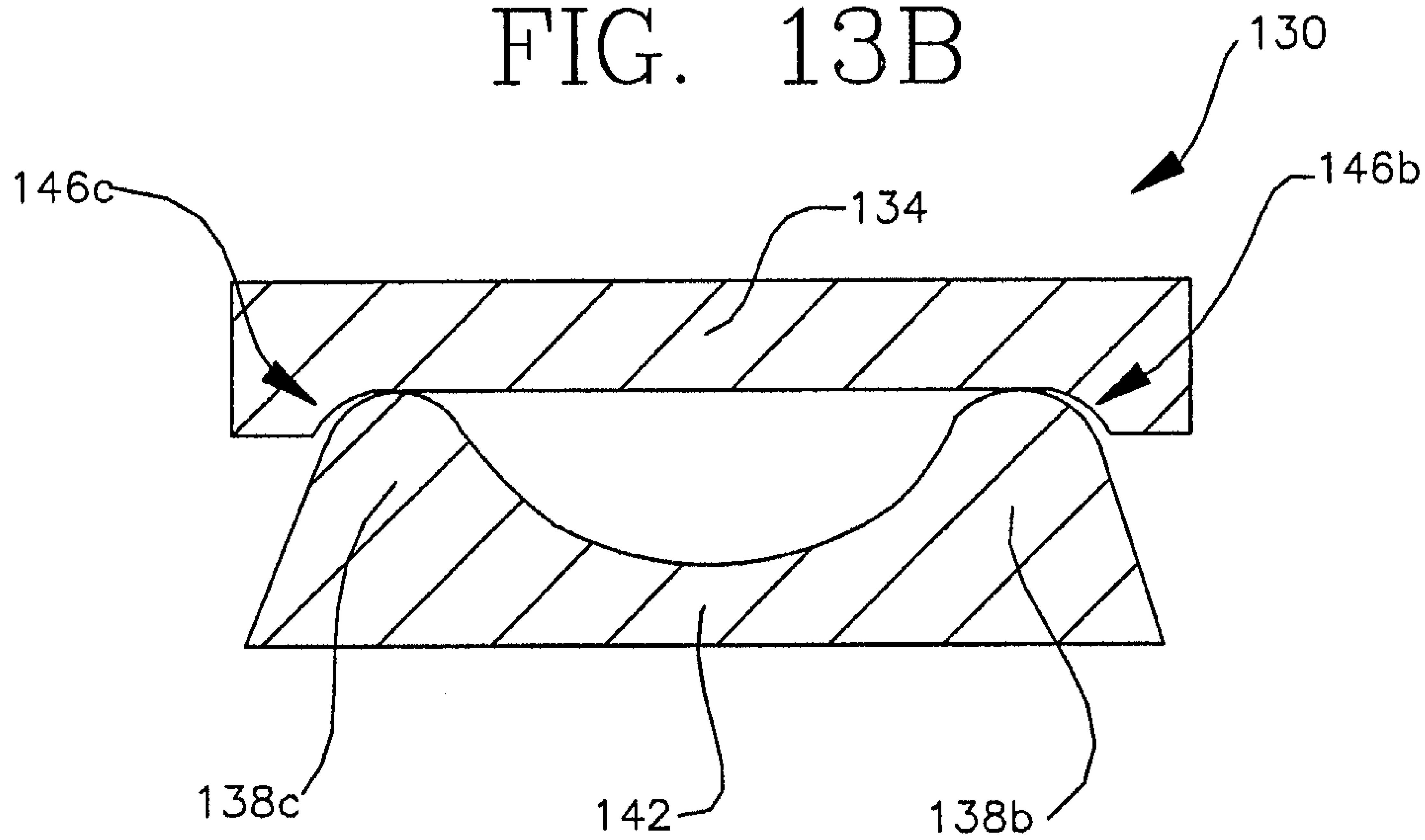


FIG. 13C

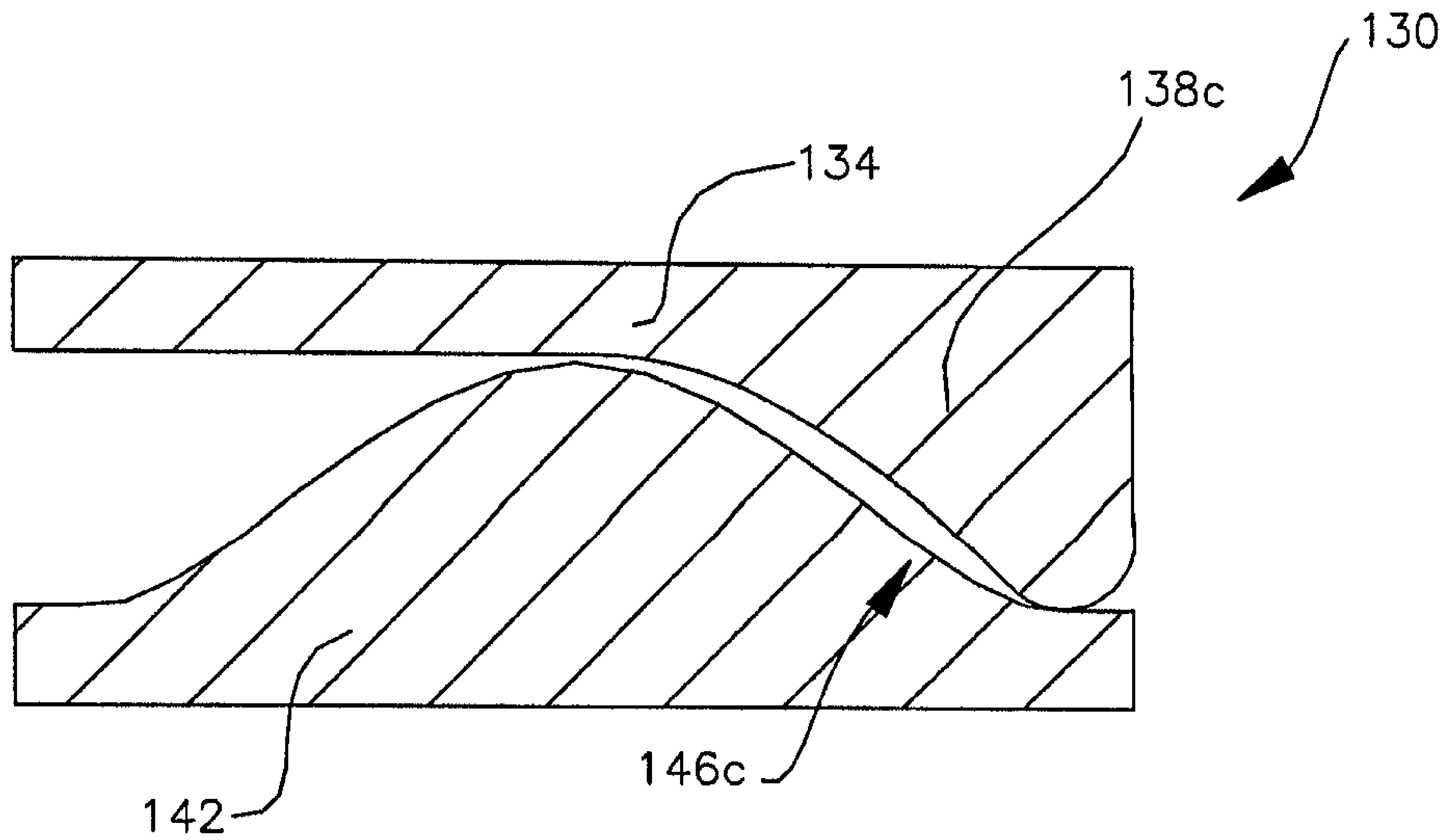


FIG. 14A

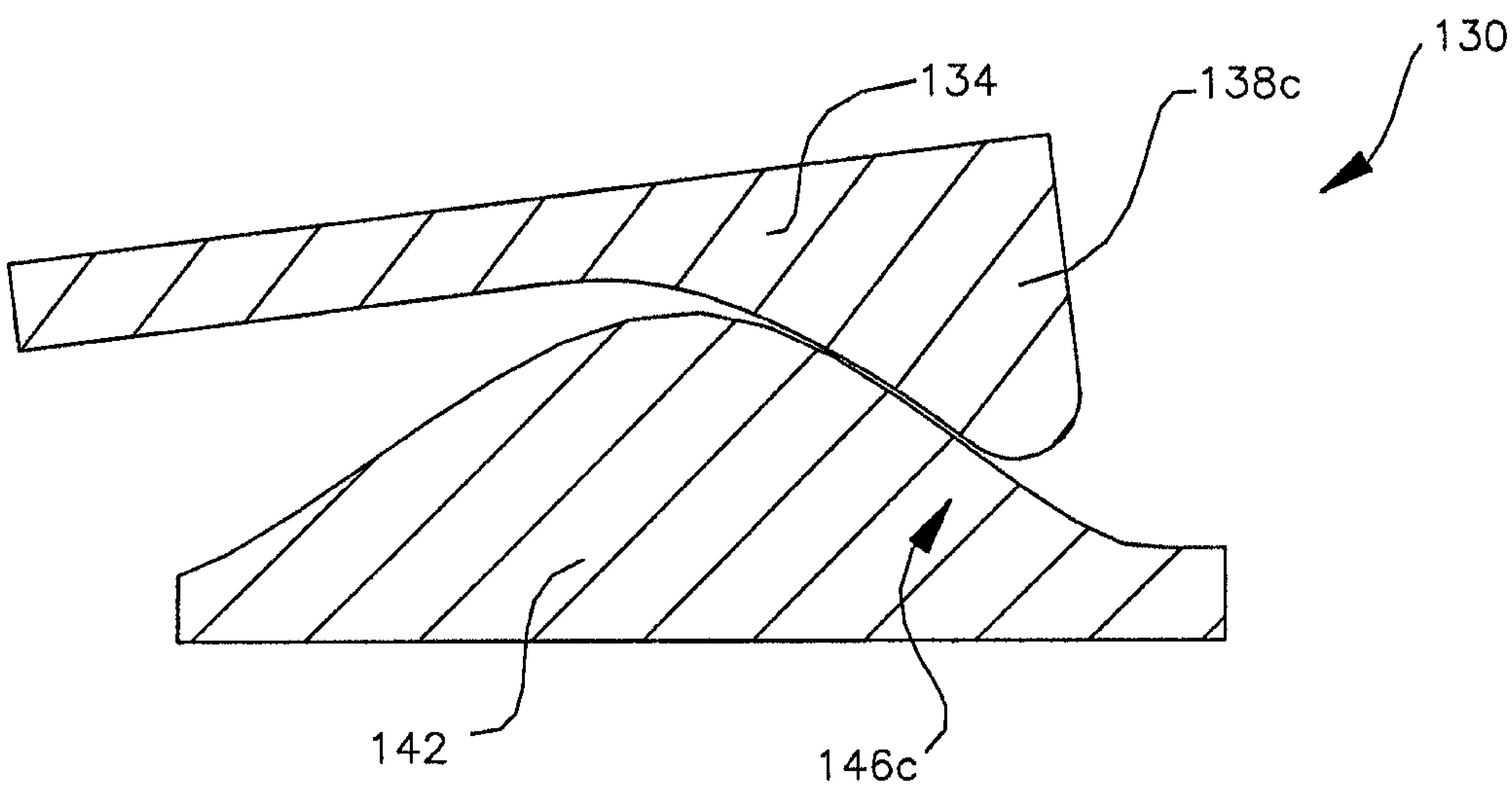


FIG. 14B

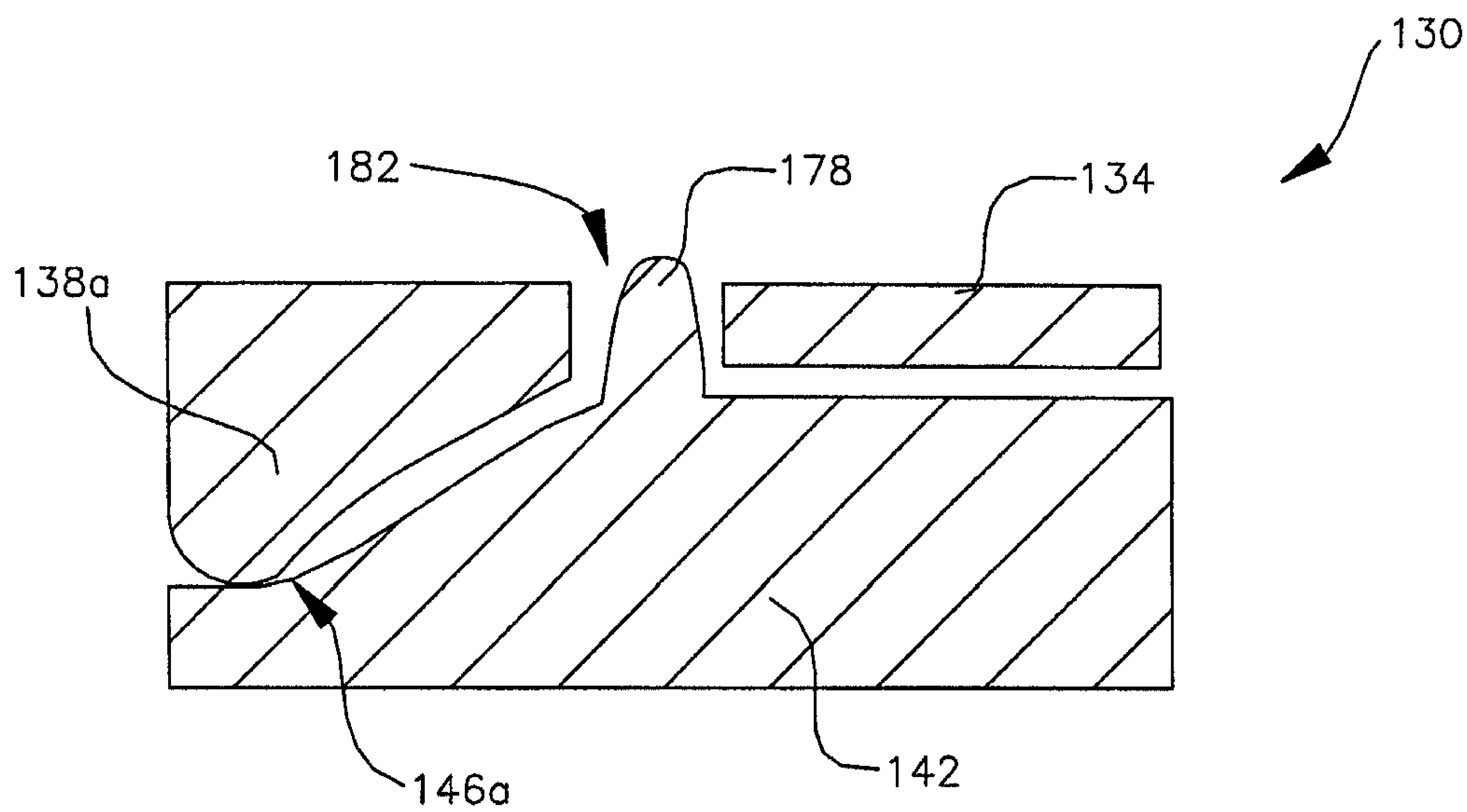


FIG. 15

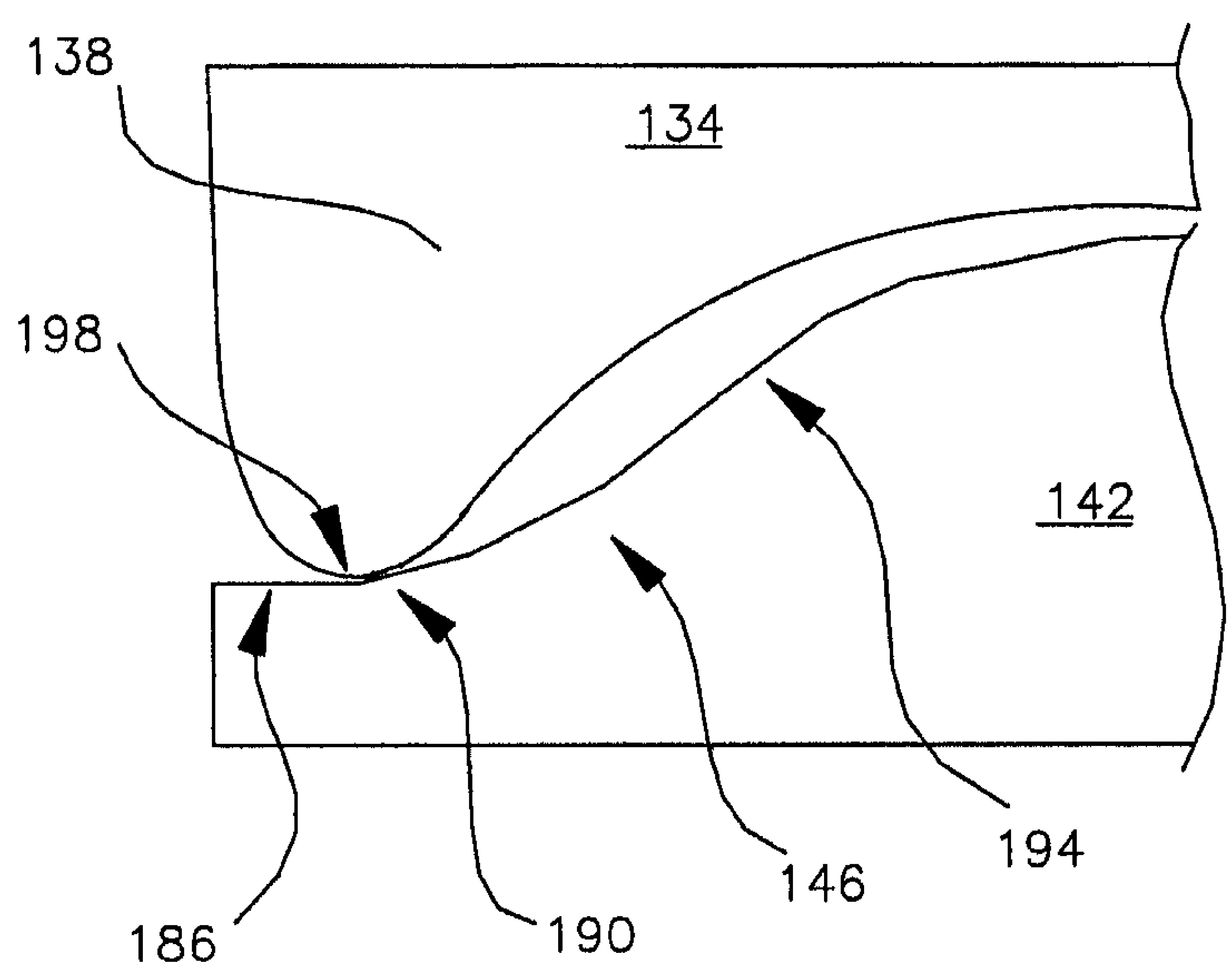
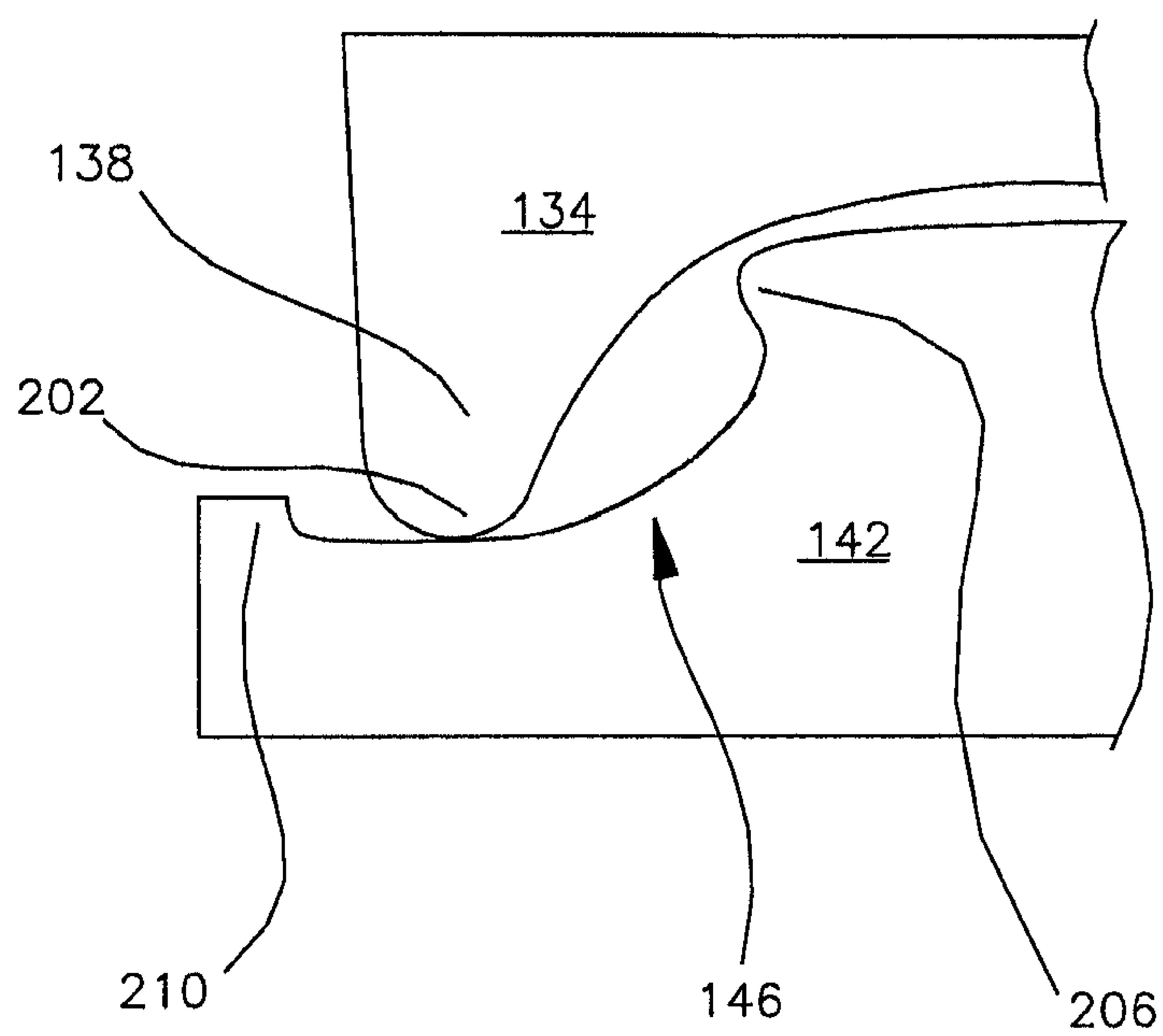


FIG. 16



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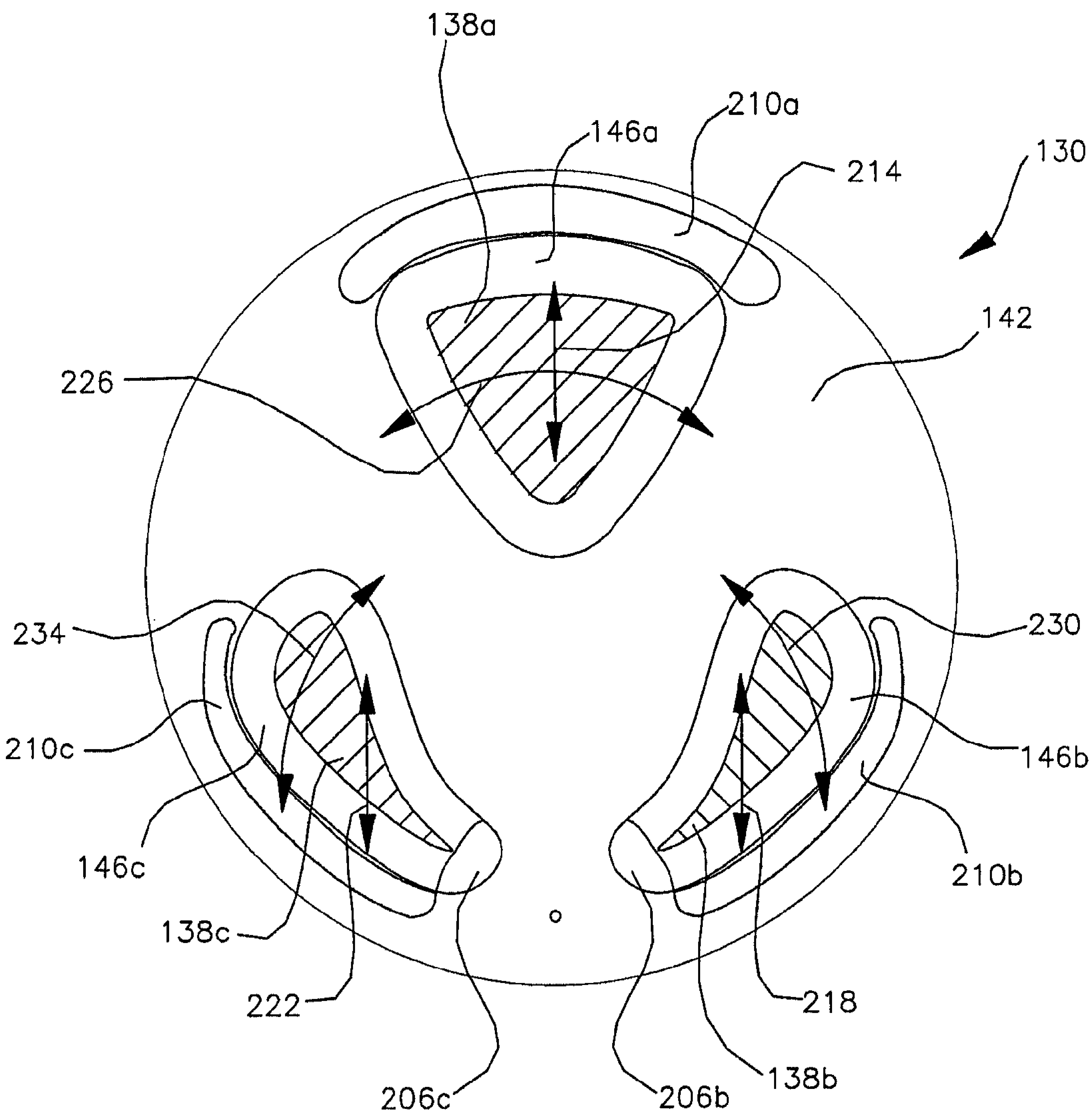
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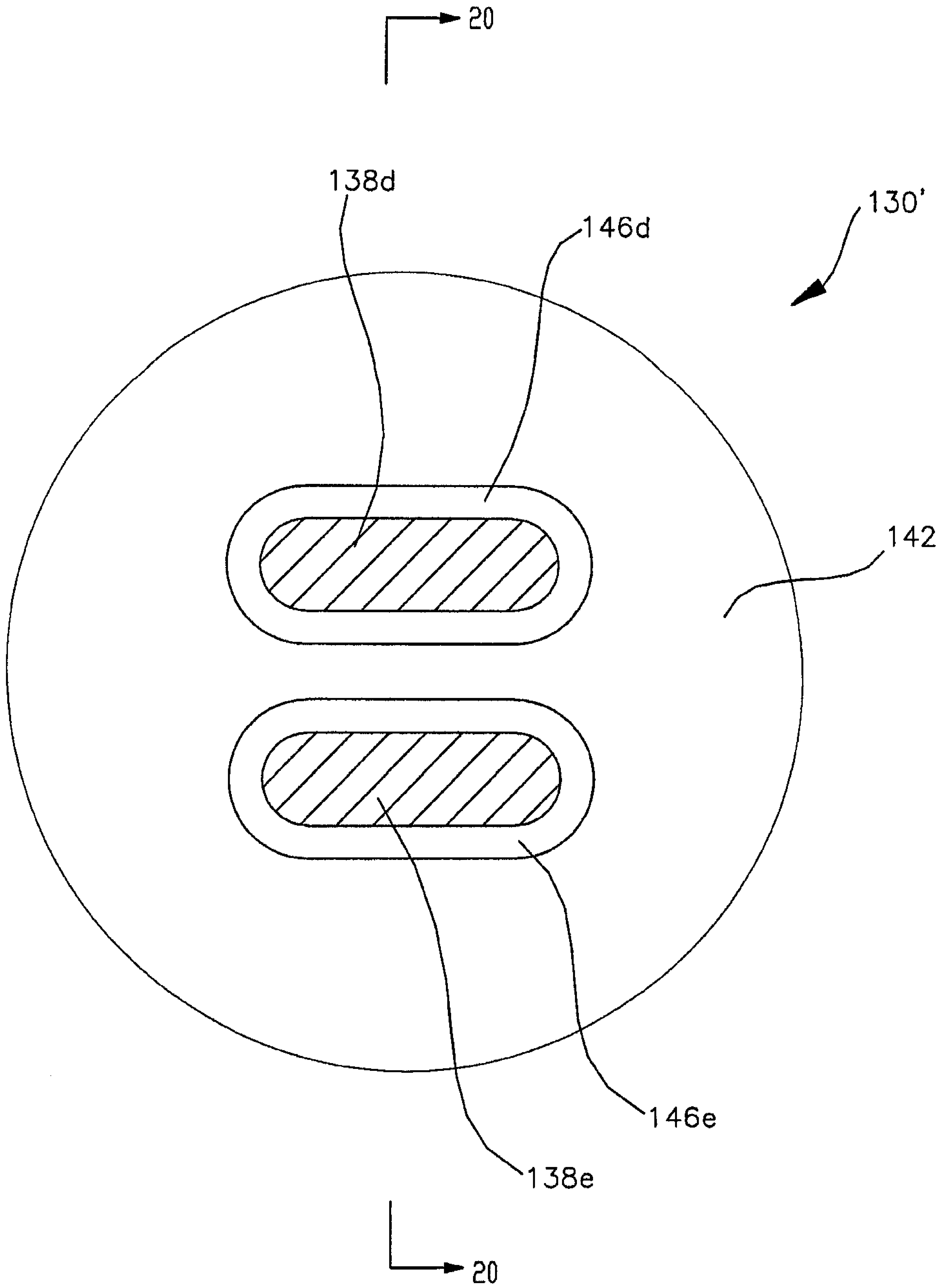
FIG. 18



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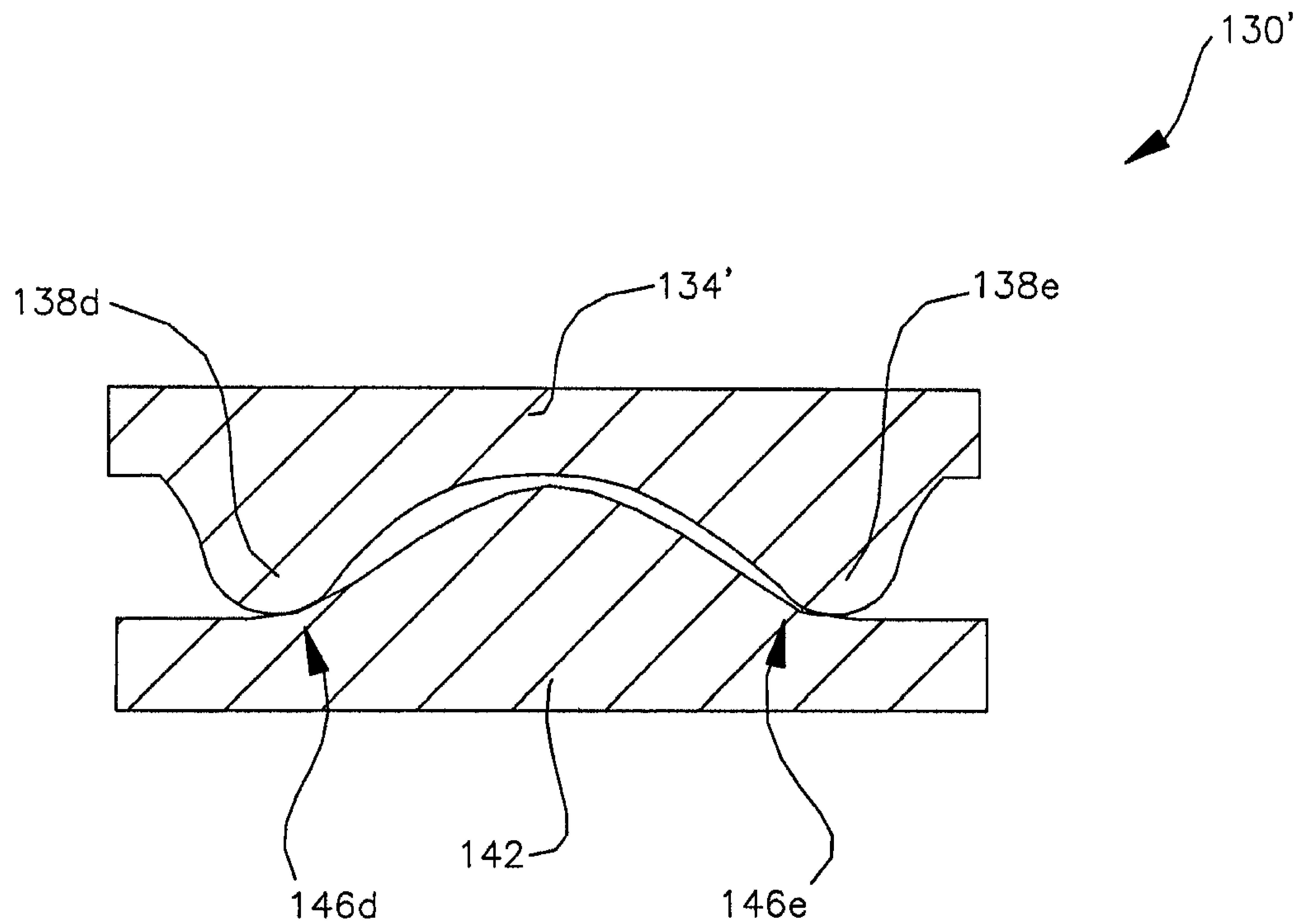

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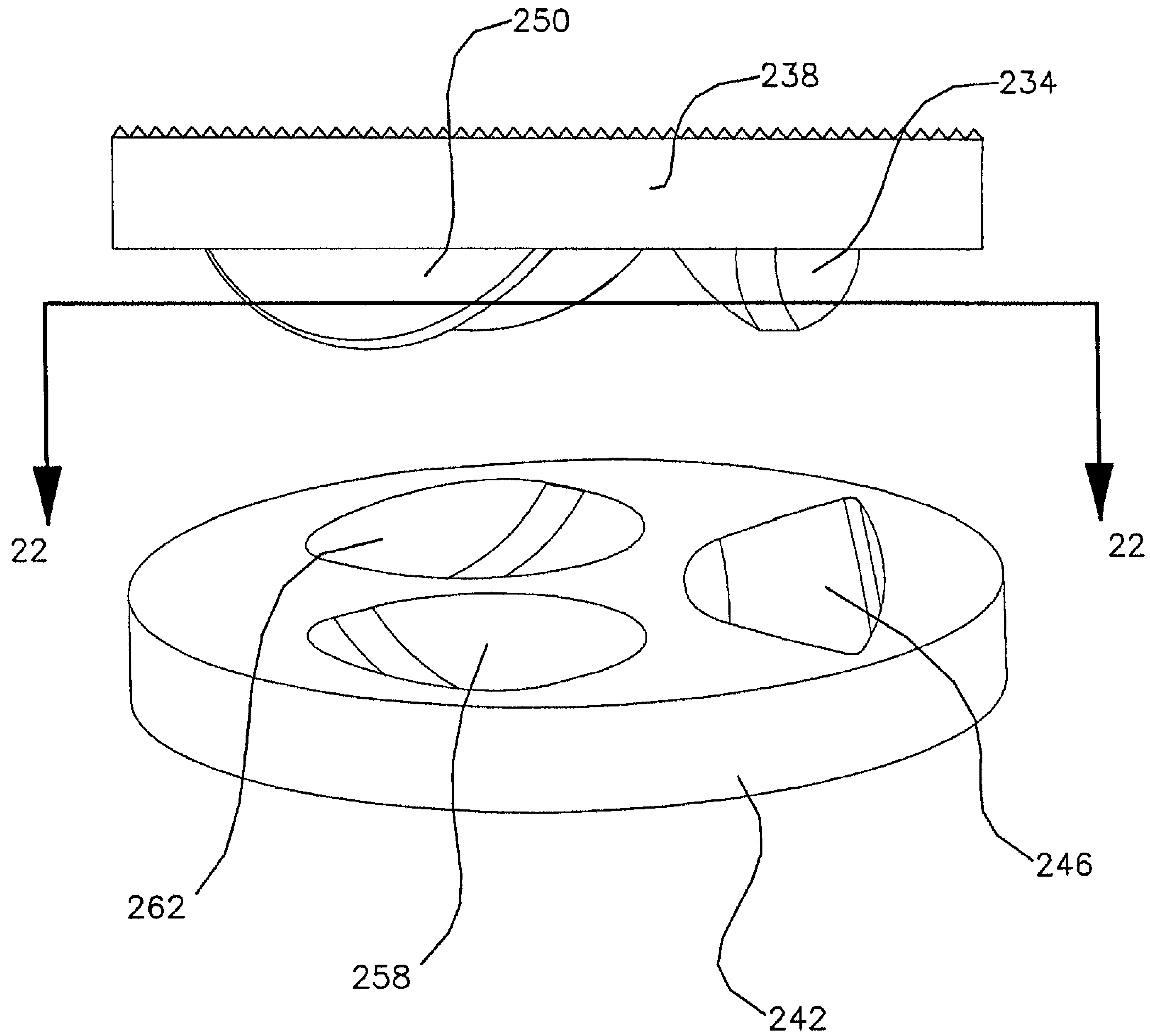
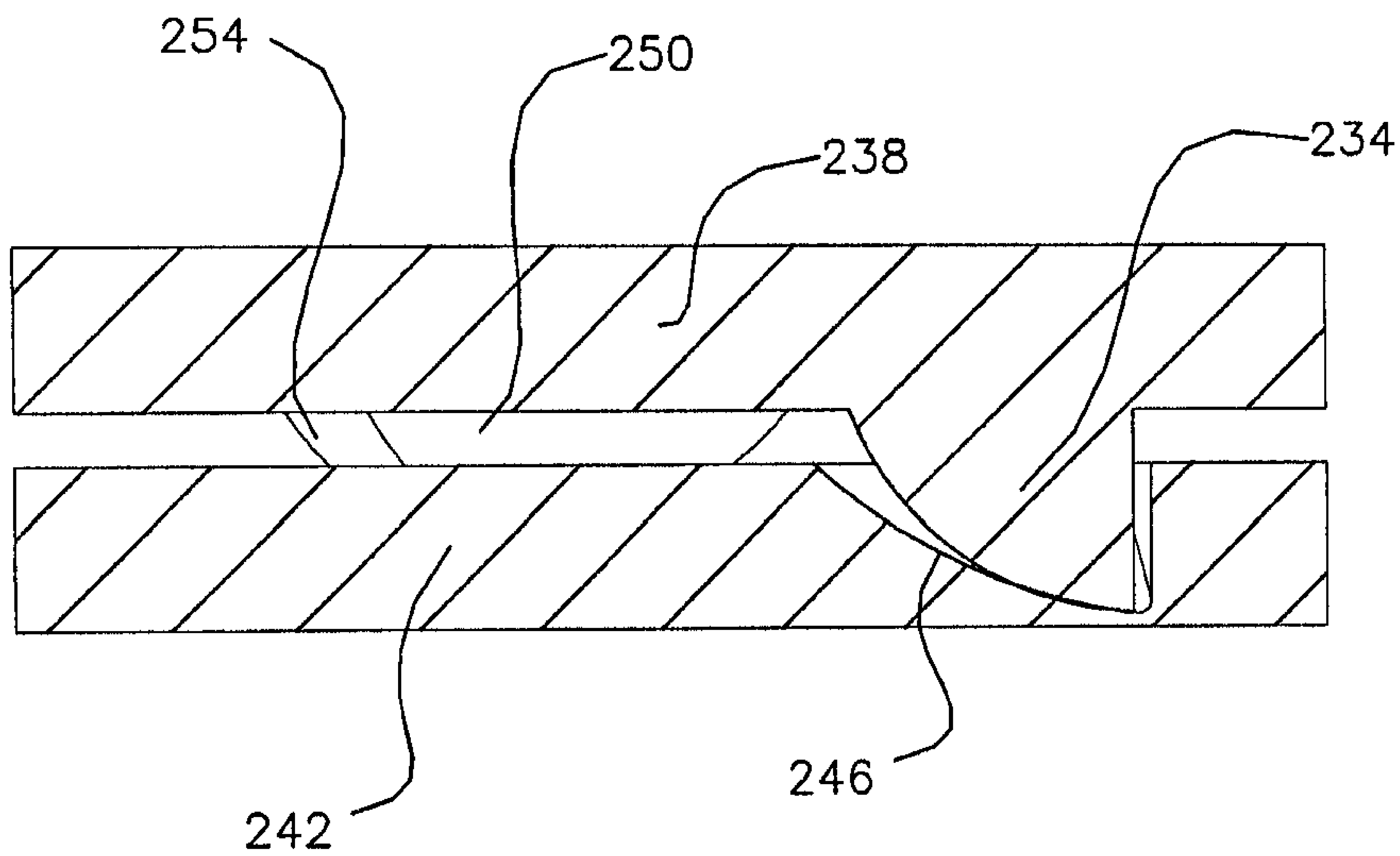


FIG. 21



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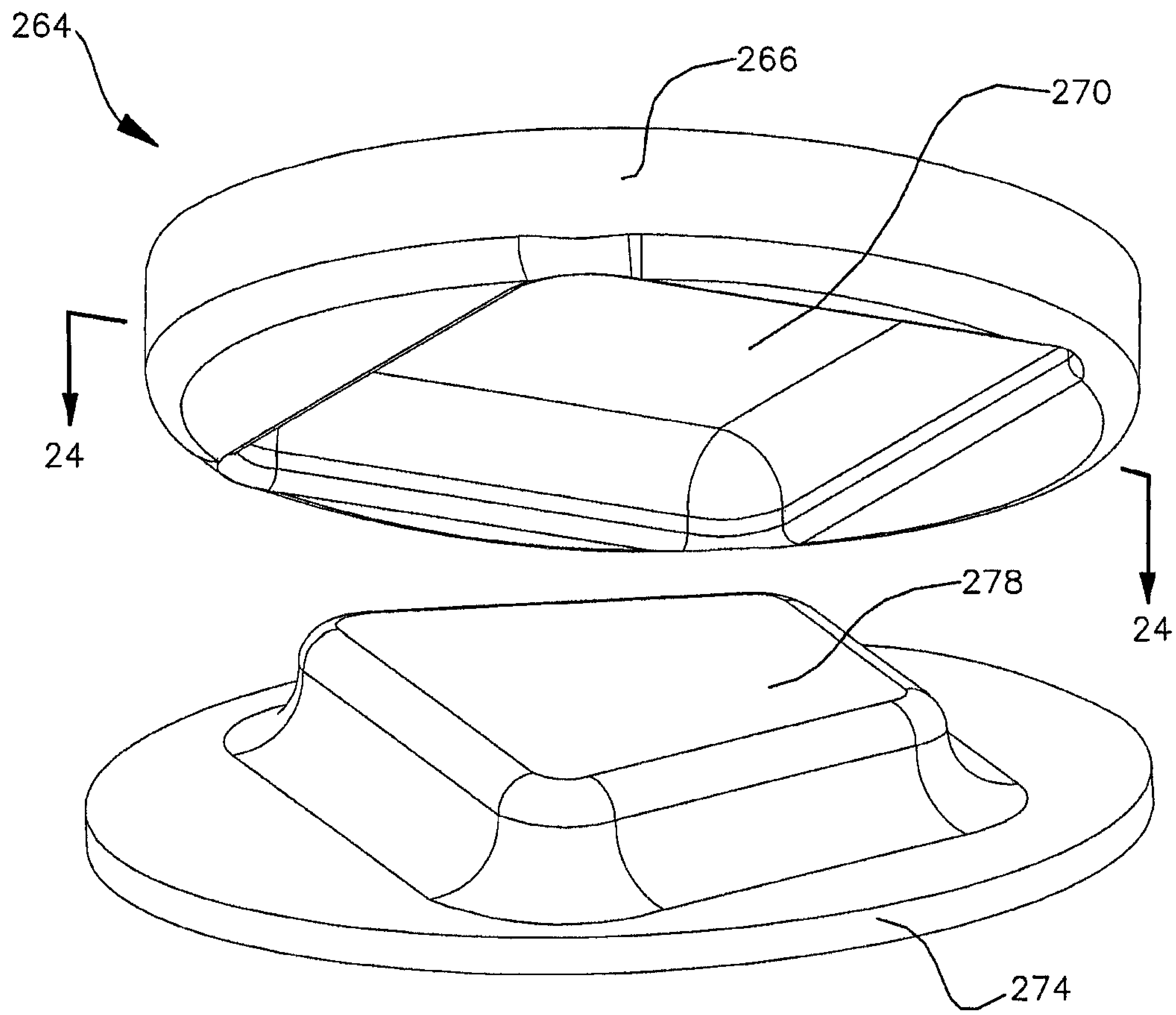


FIG. 23

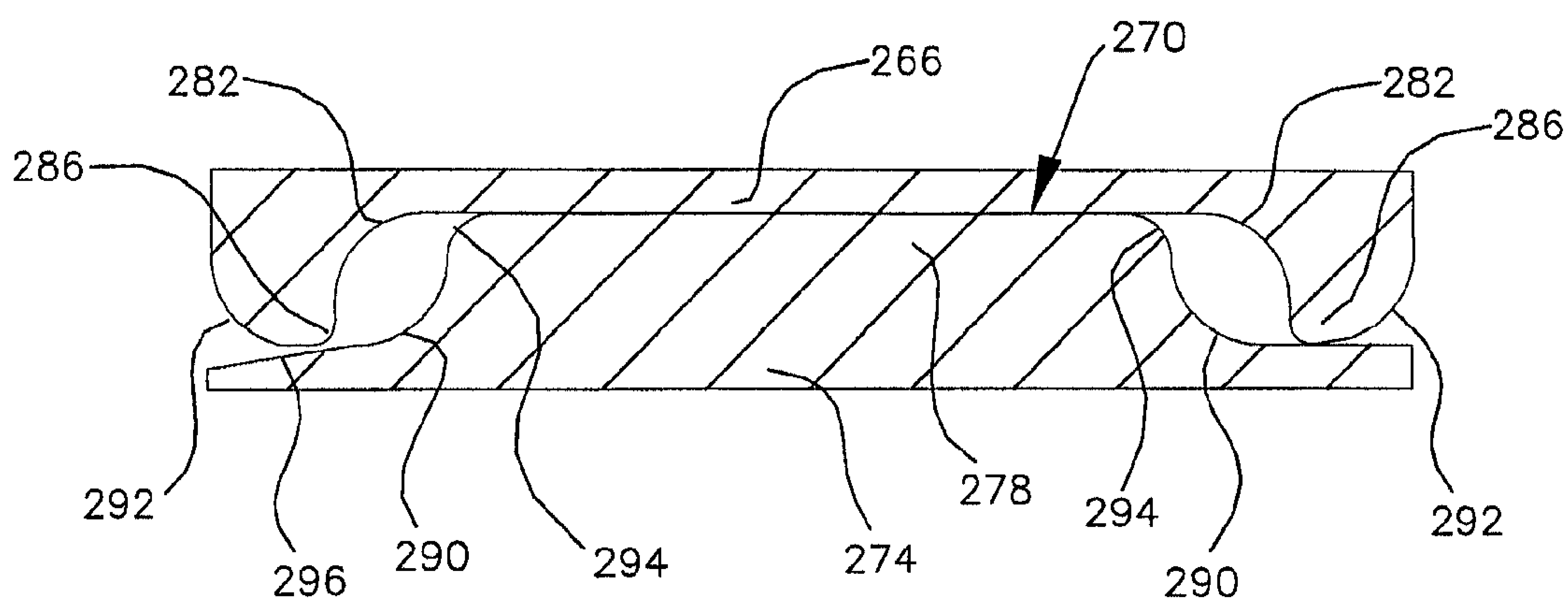
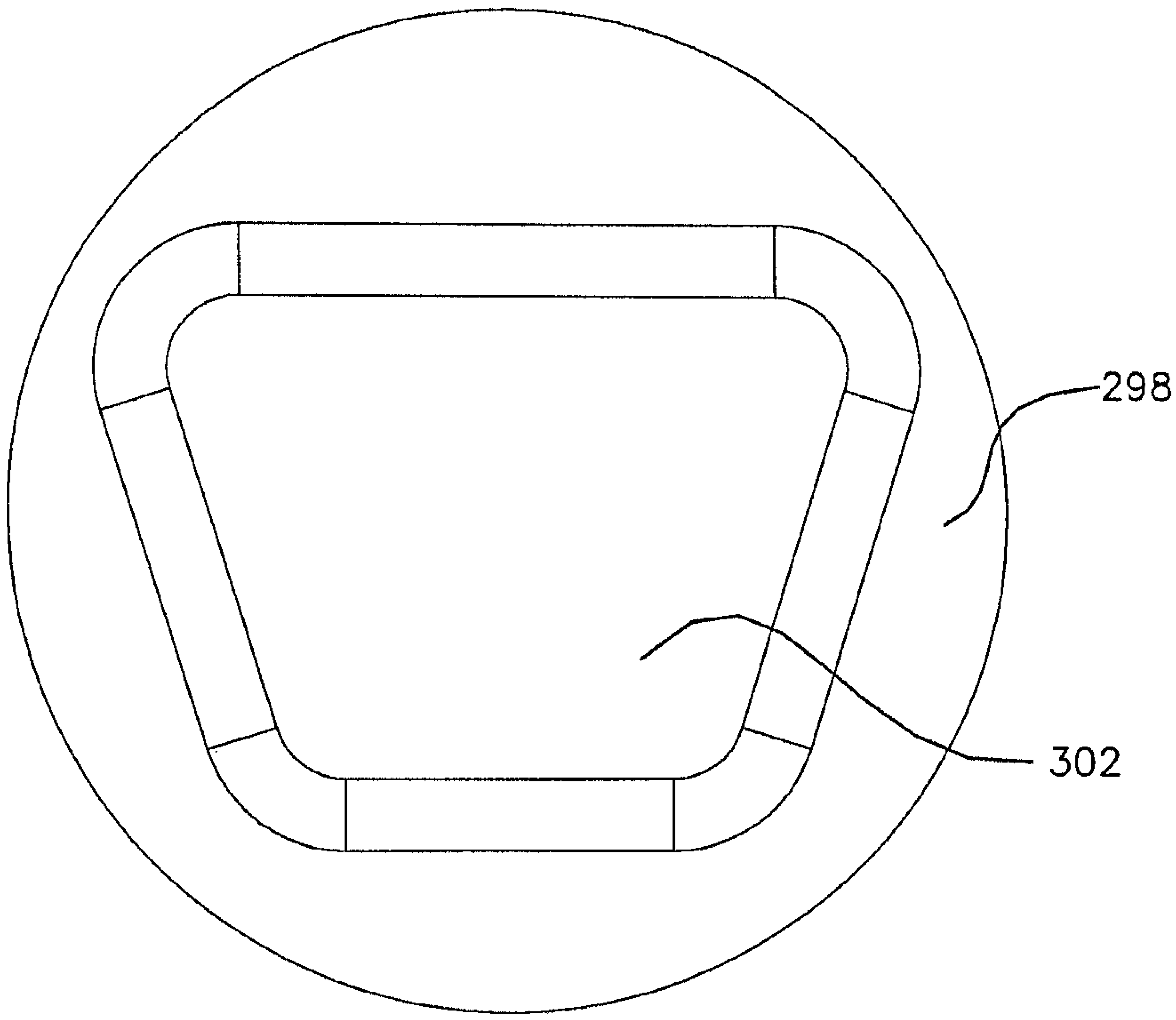


FIG. 24



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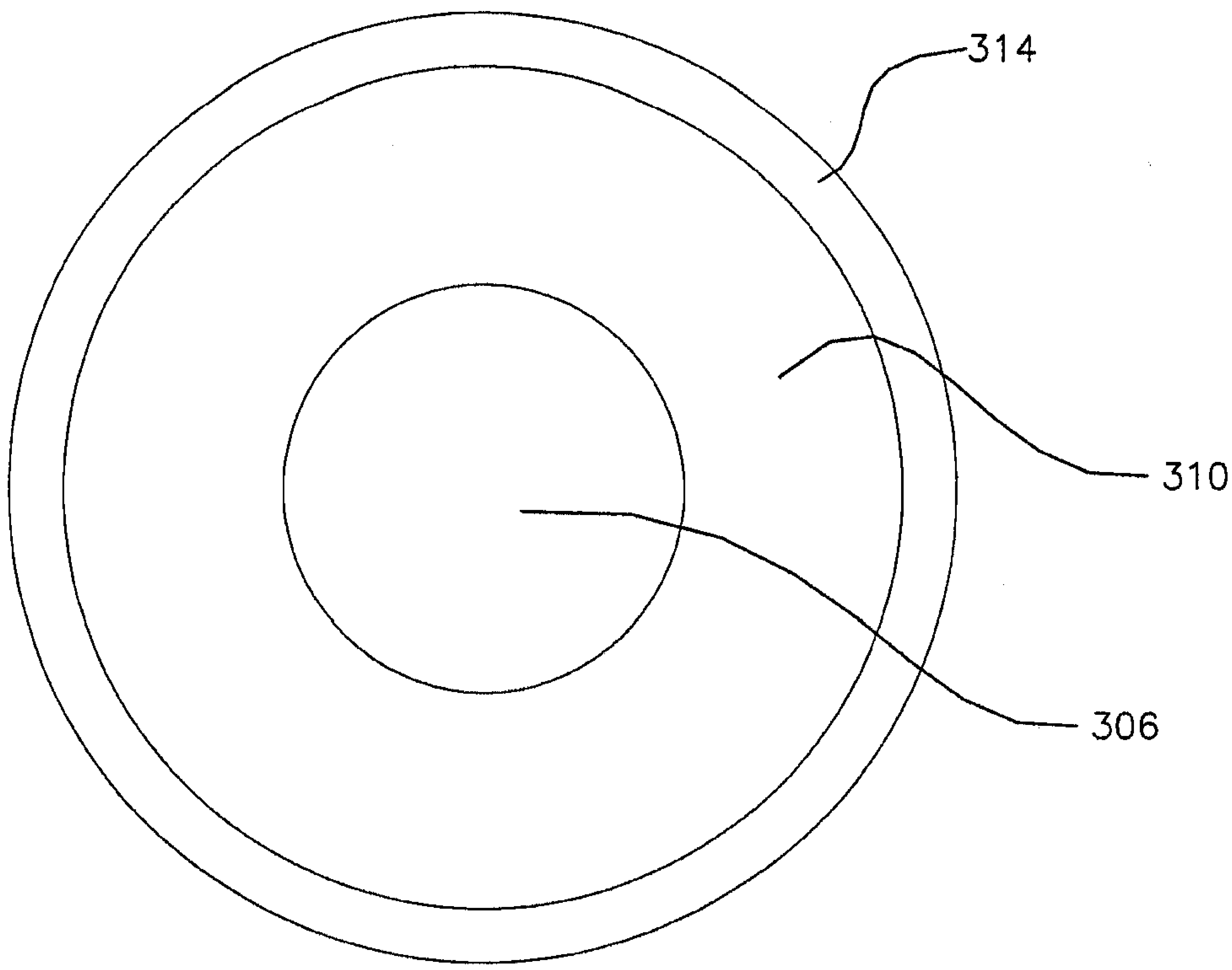
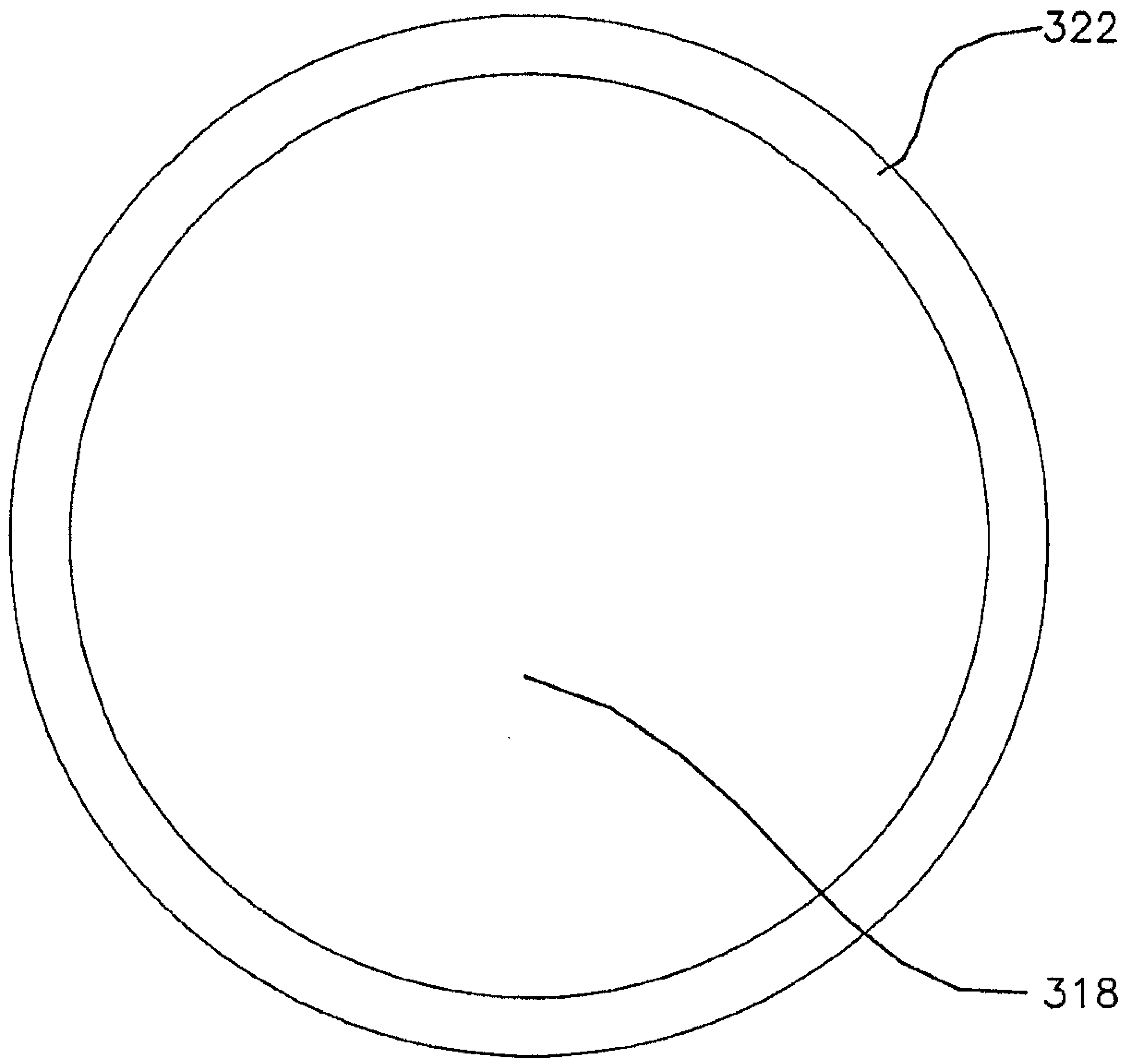


FIG. 26



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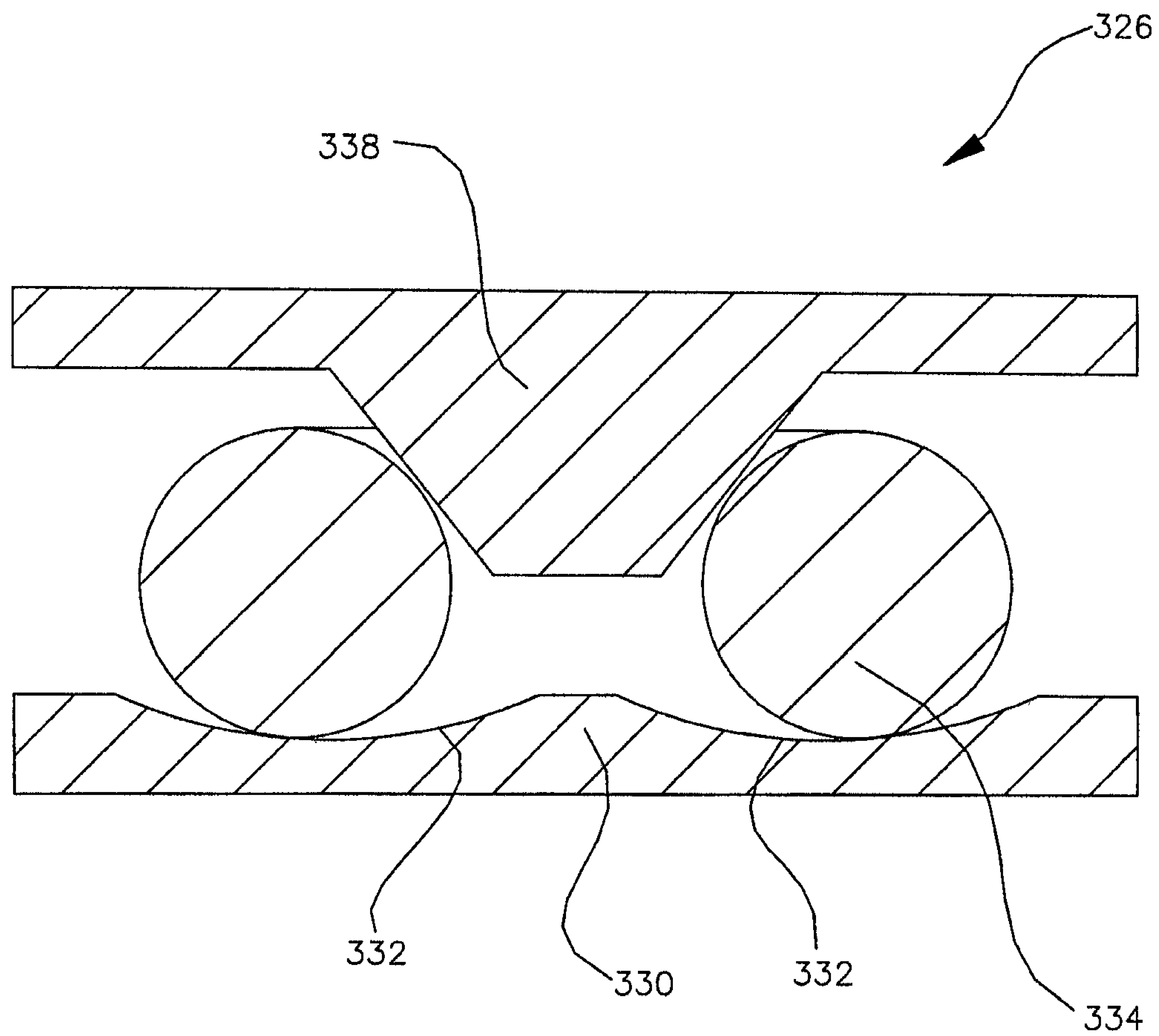

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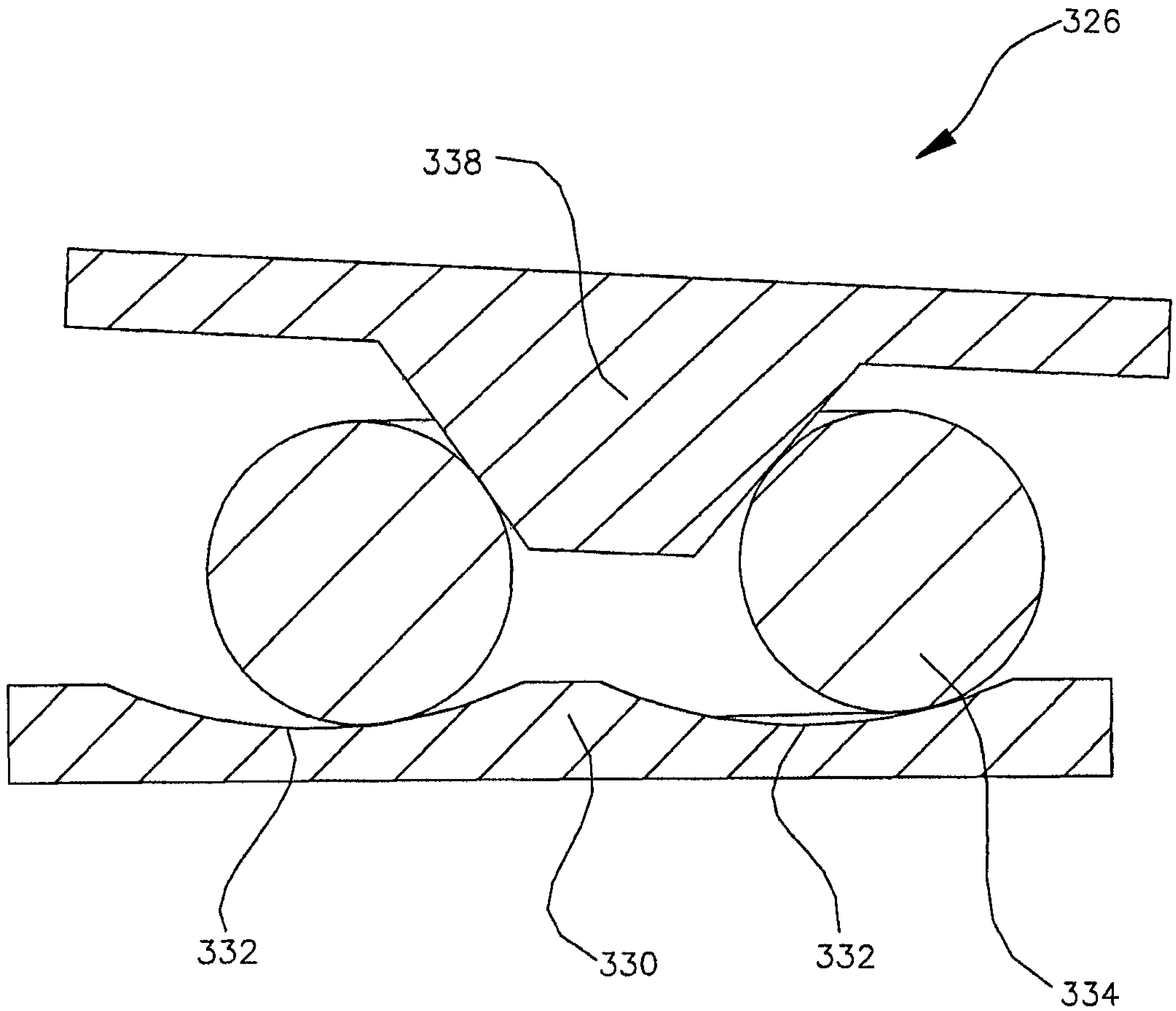
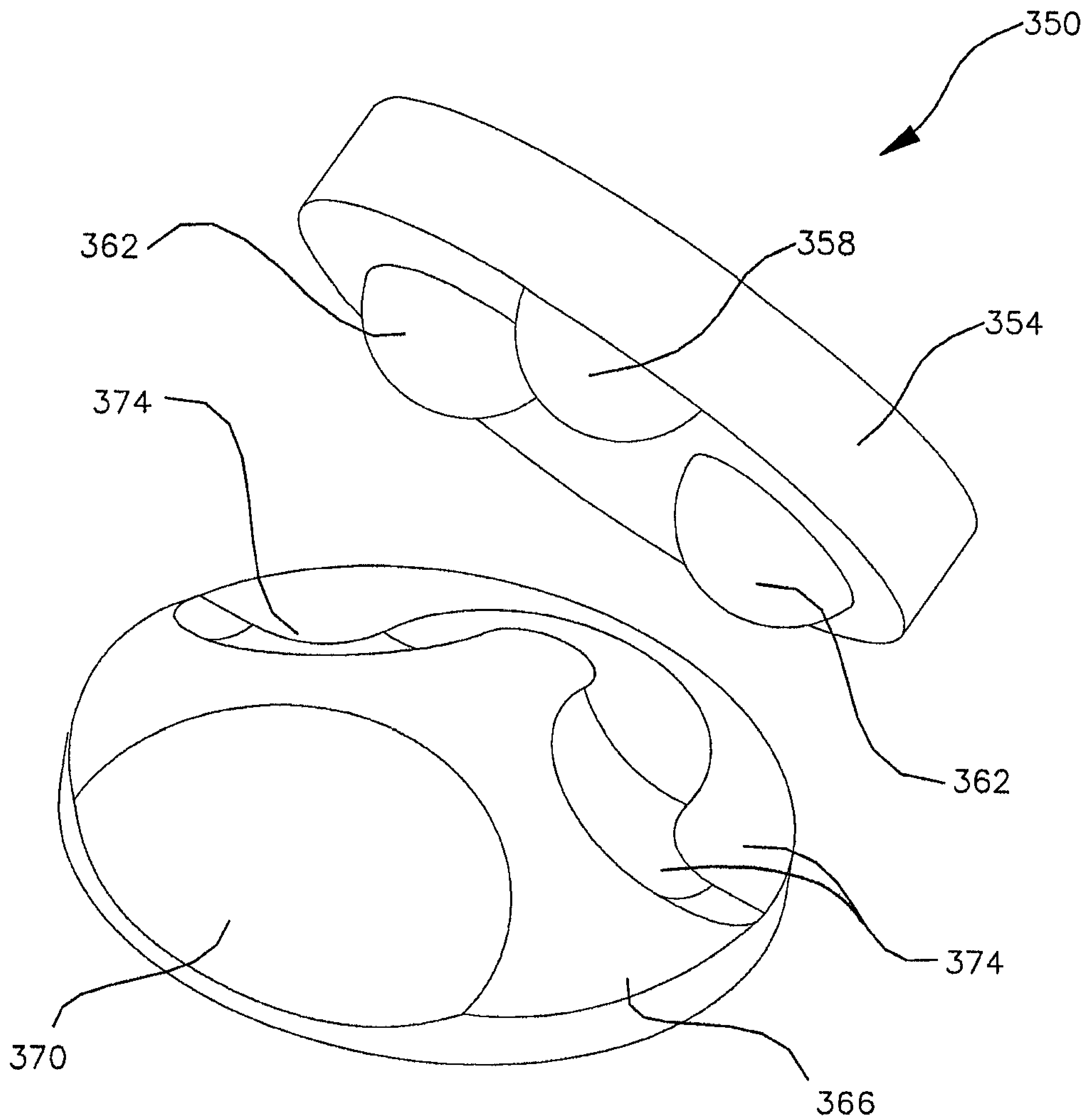


FIG. 29



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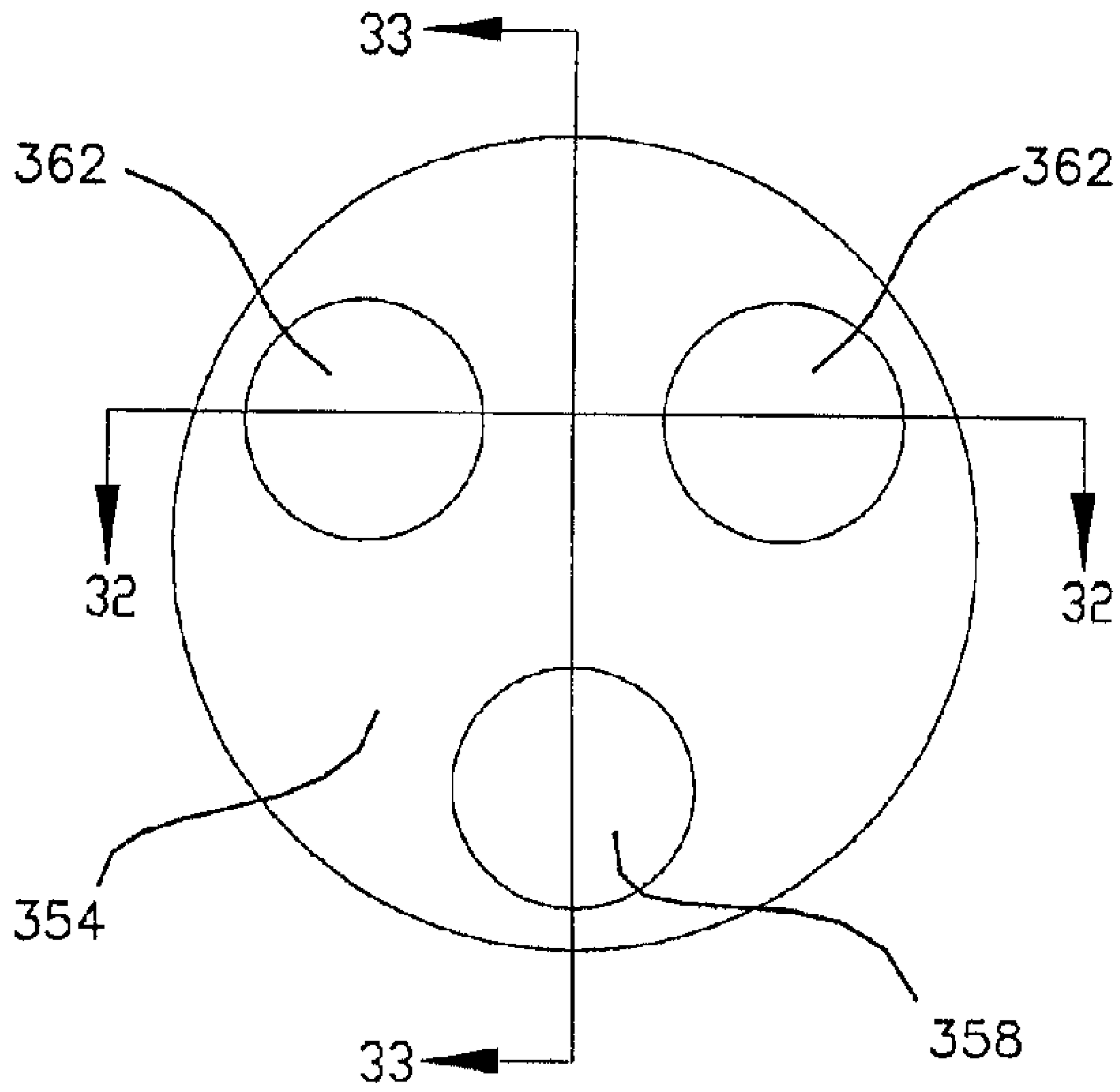

FIG. 31

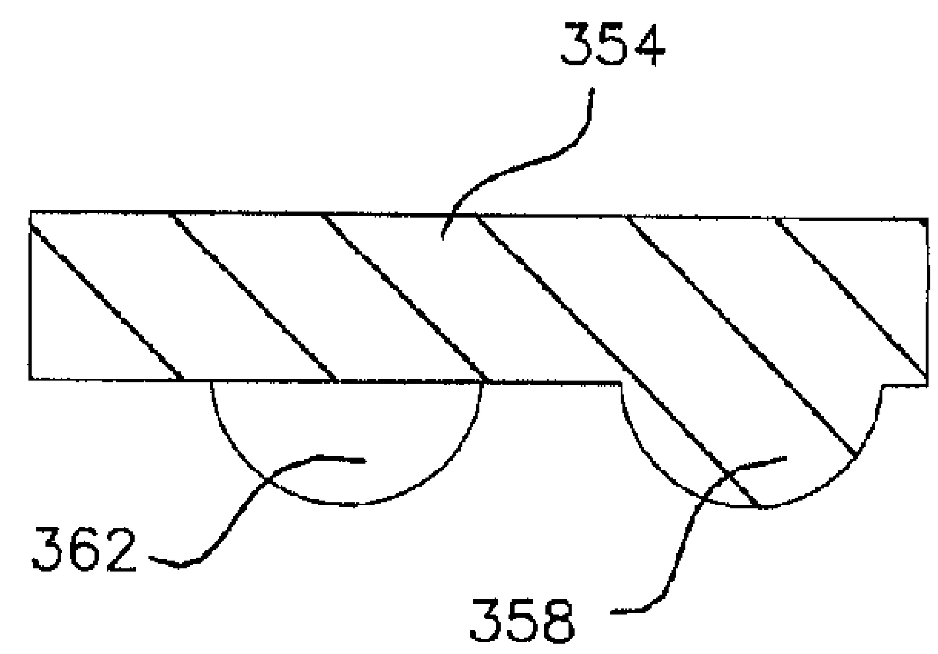

FIG. 33

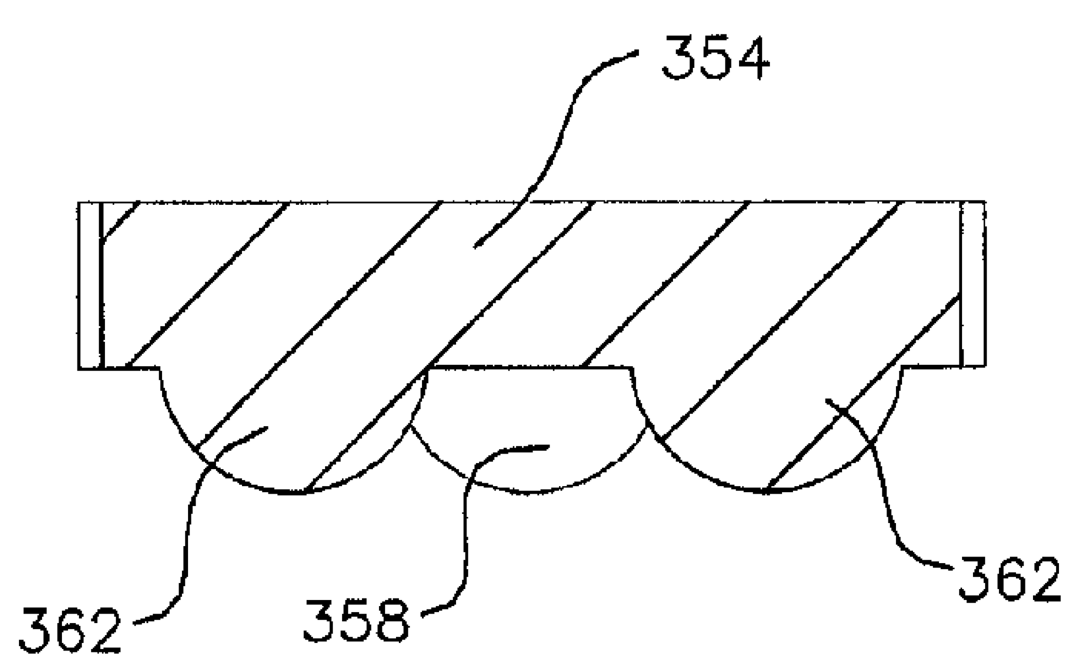

FIG. 32

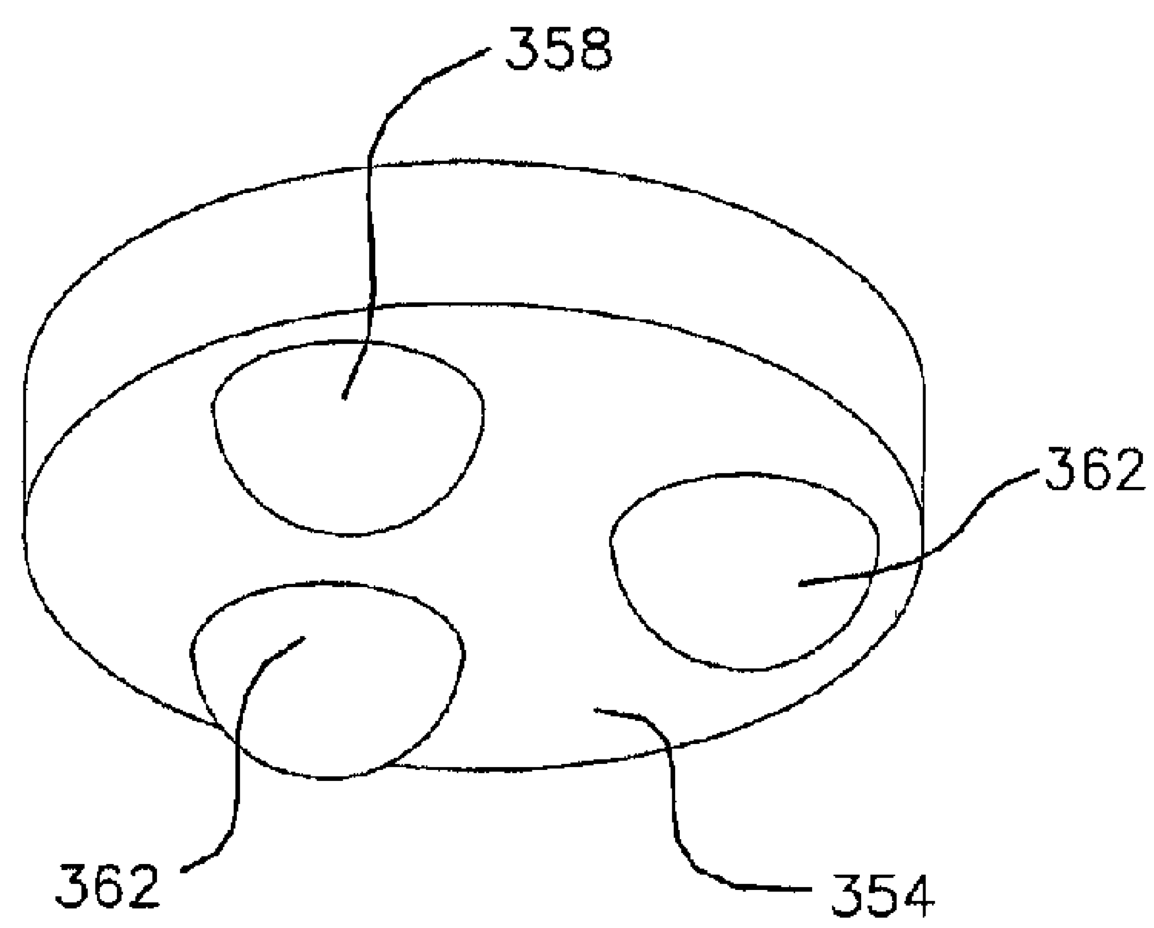

FIG. 34

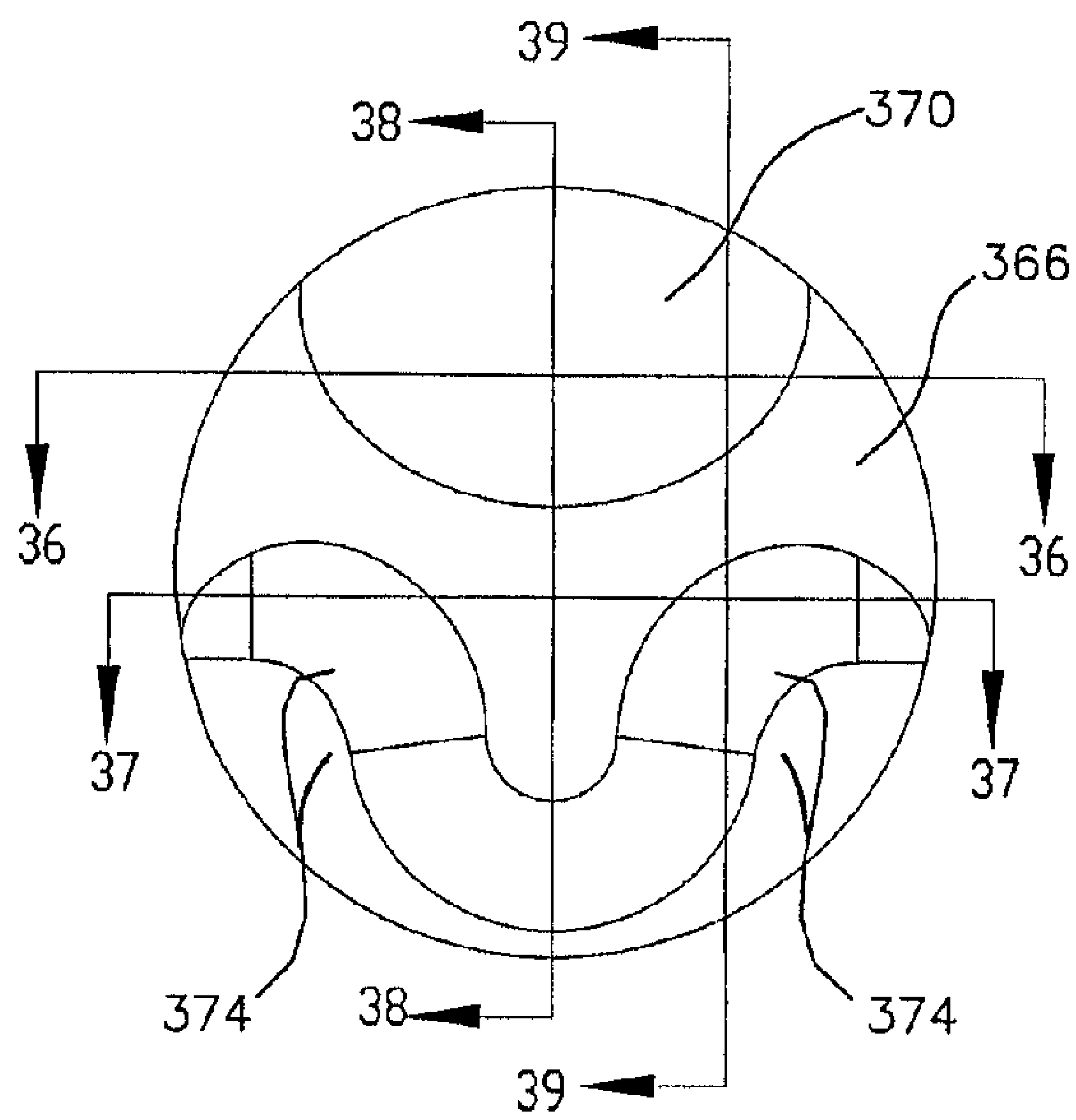

FIG. 35

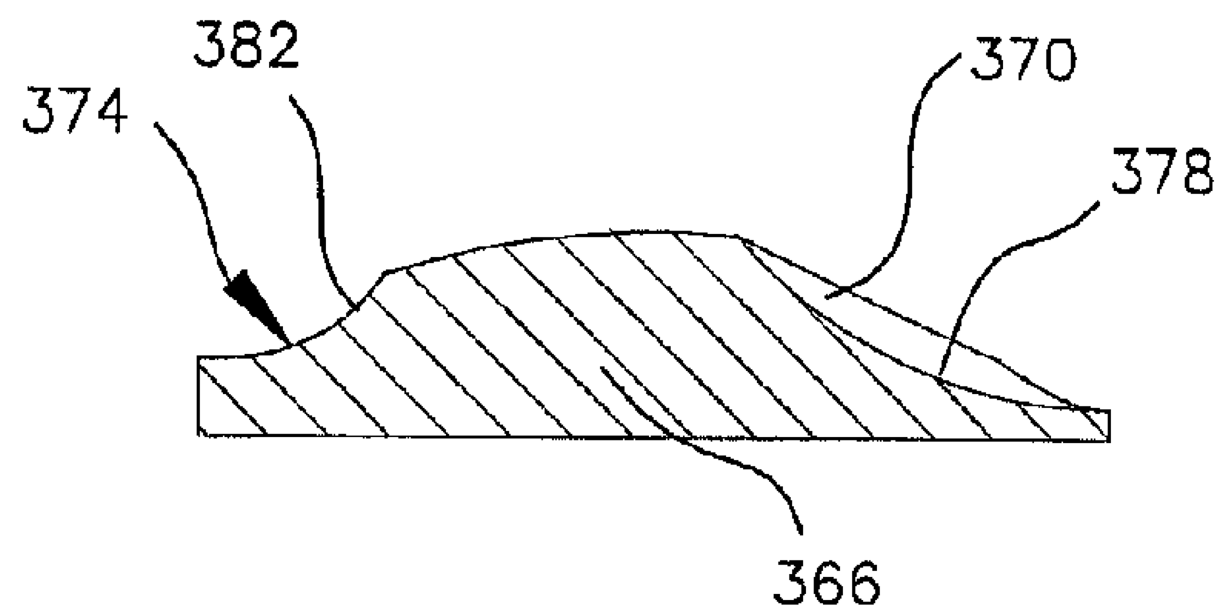

FIG. 38

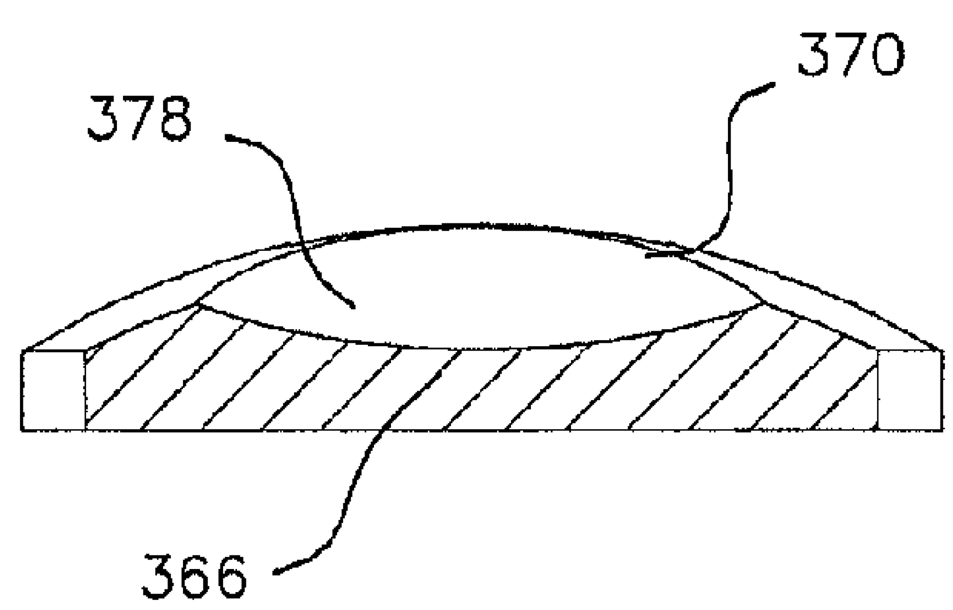

FIG. 36

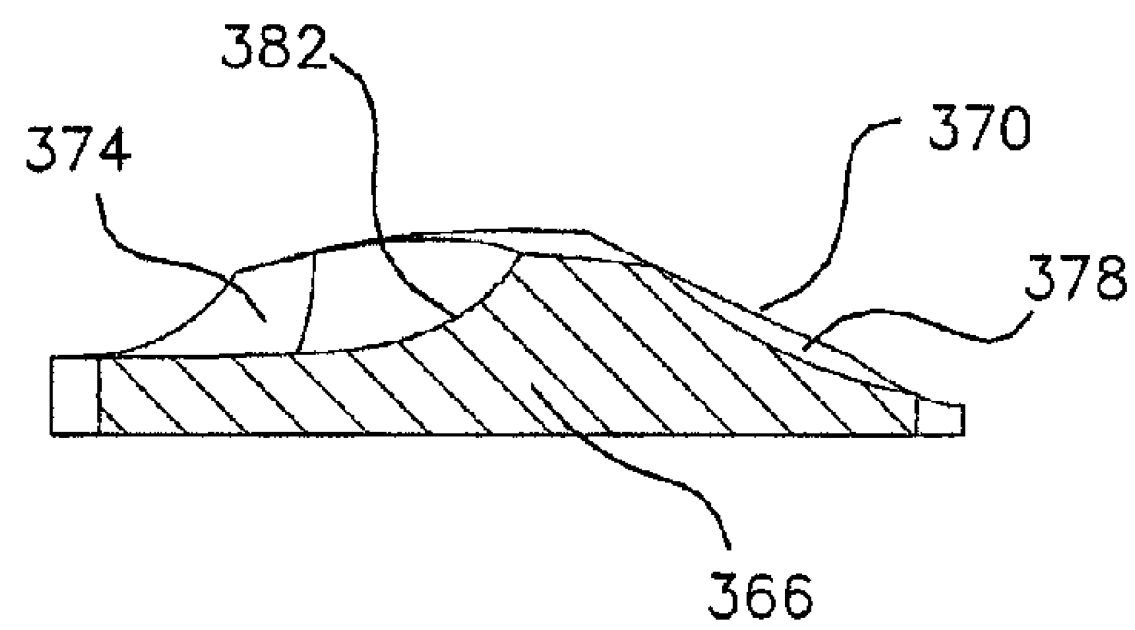

FIG. 39

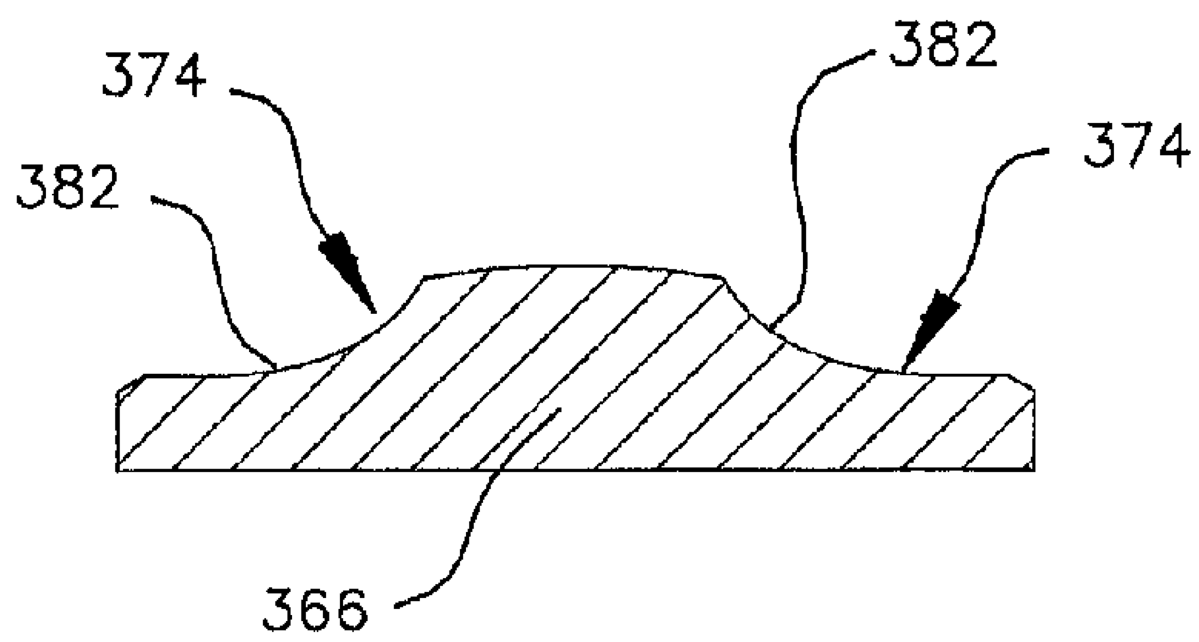

FIG. 37

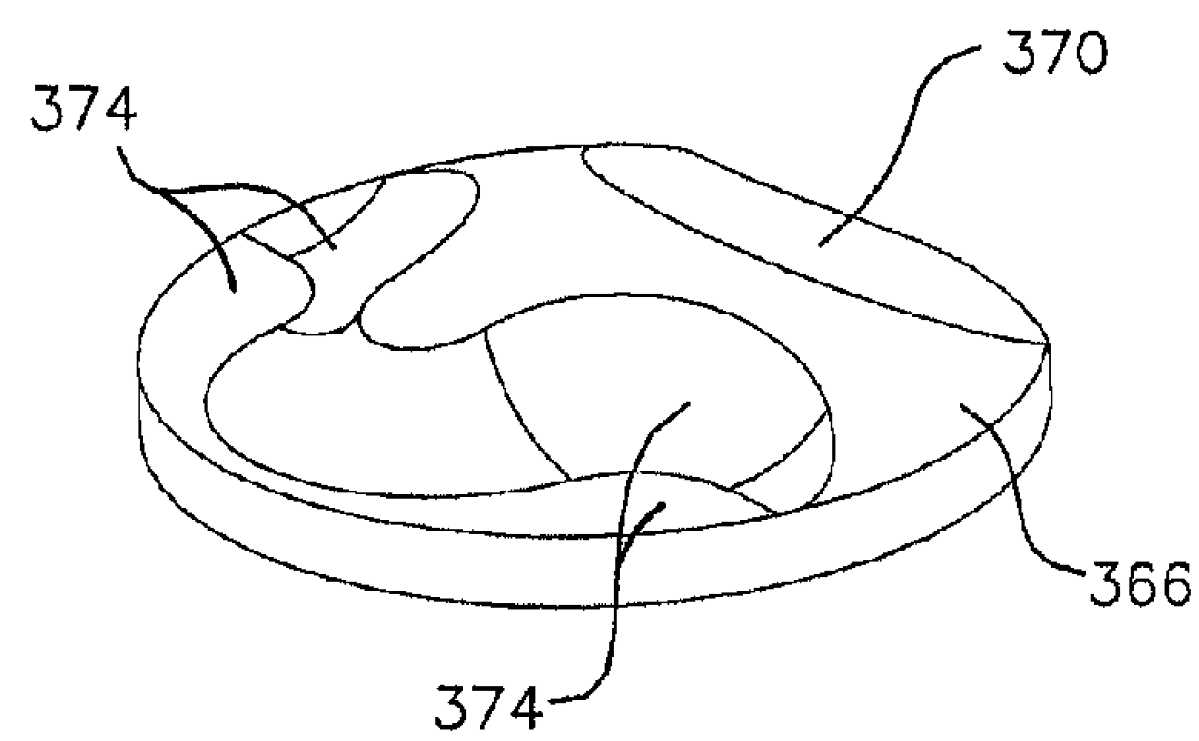

FIG. 40

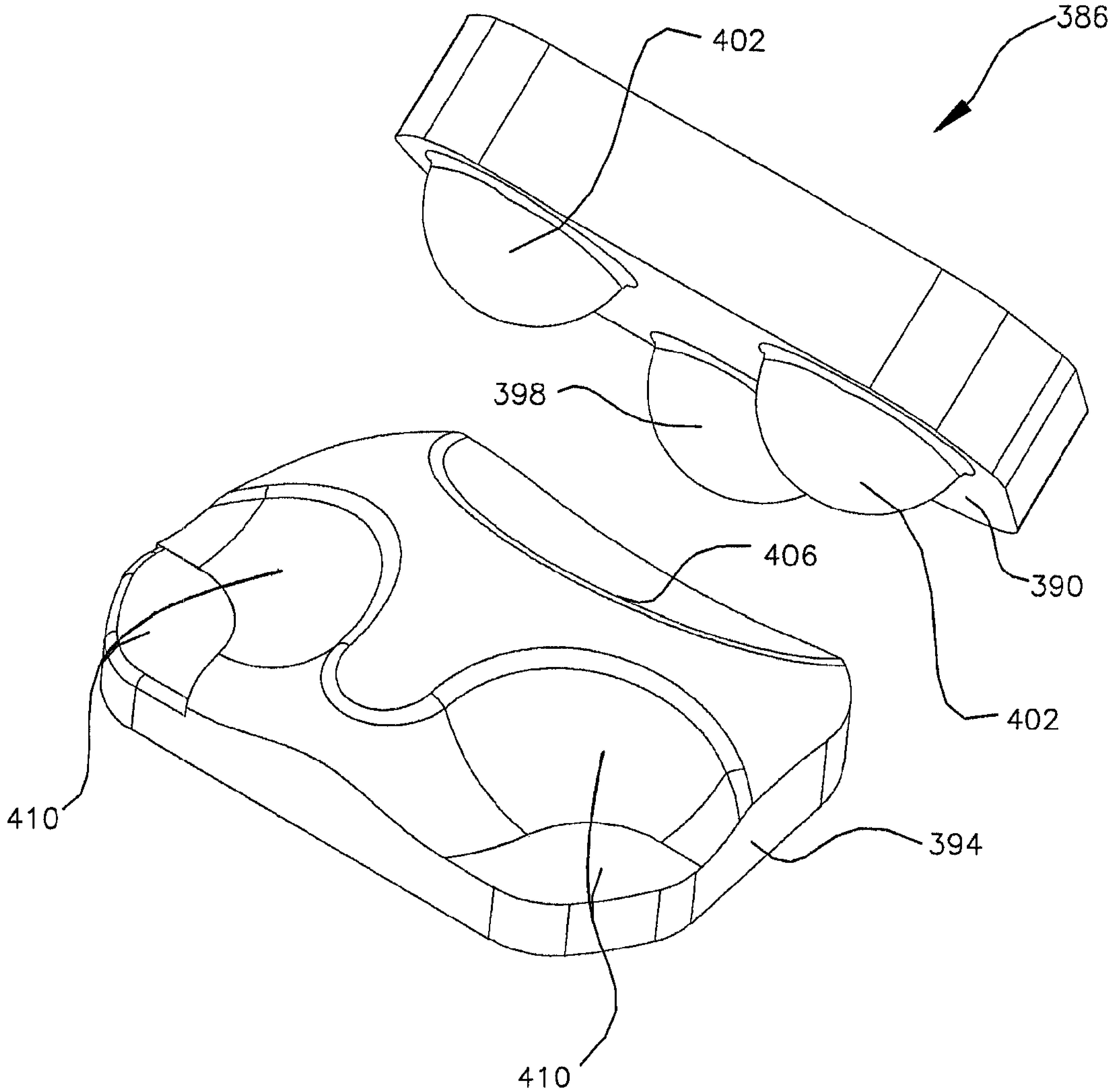

FIG. 41

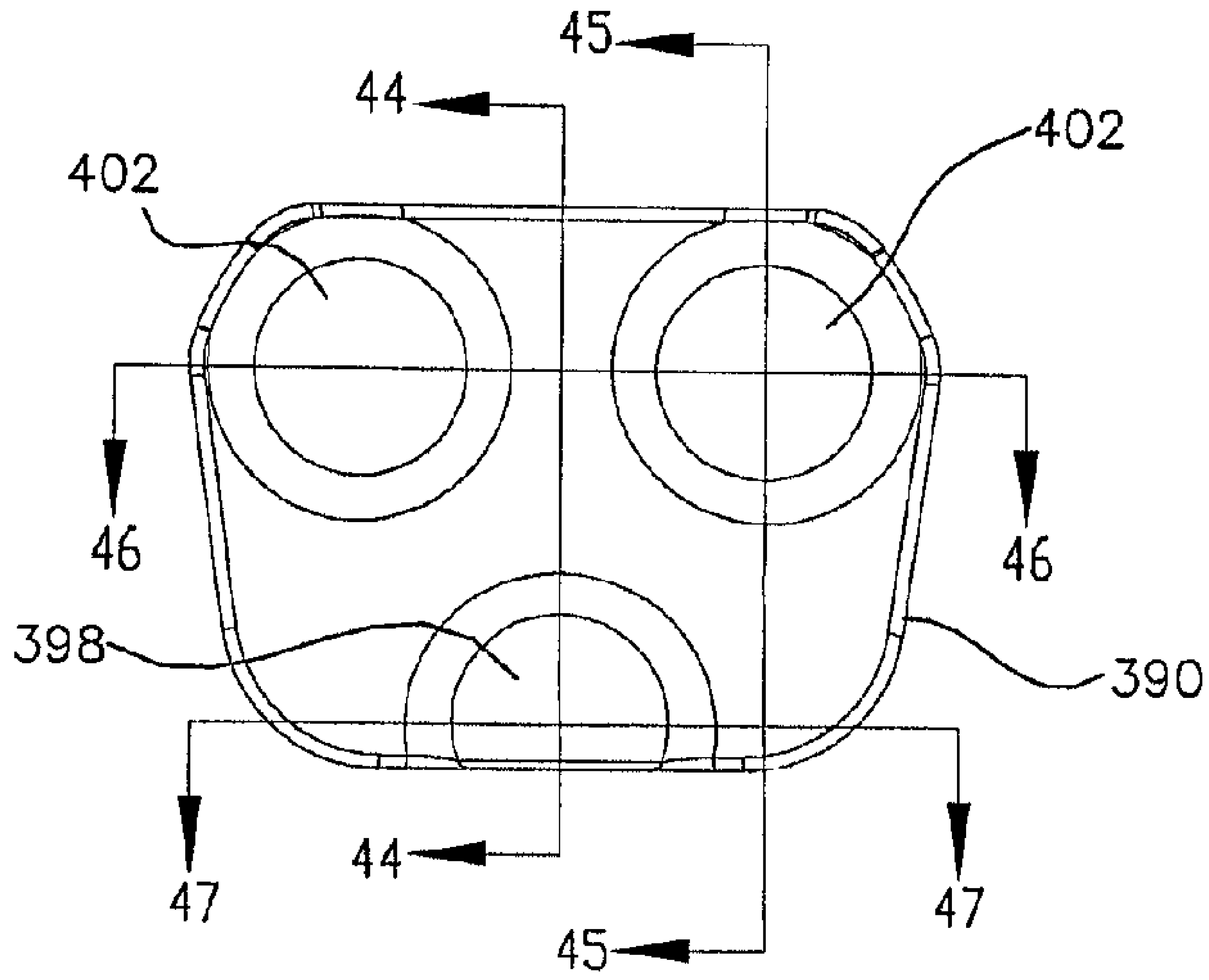

FIG. 43

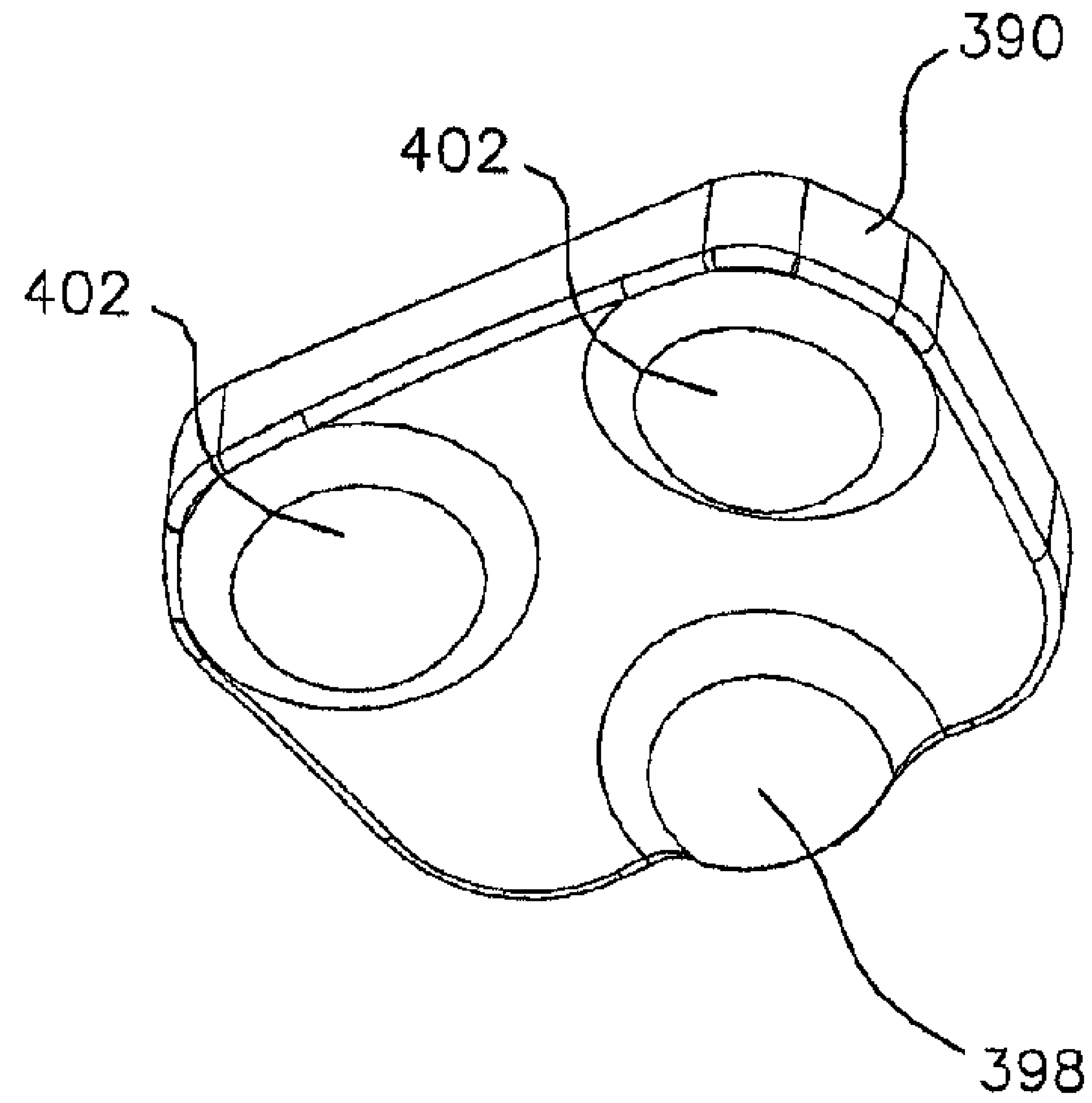

FIG. 42

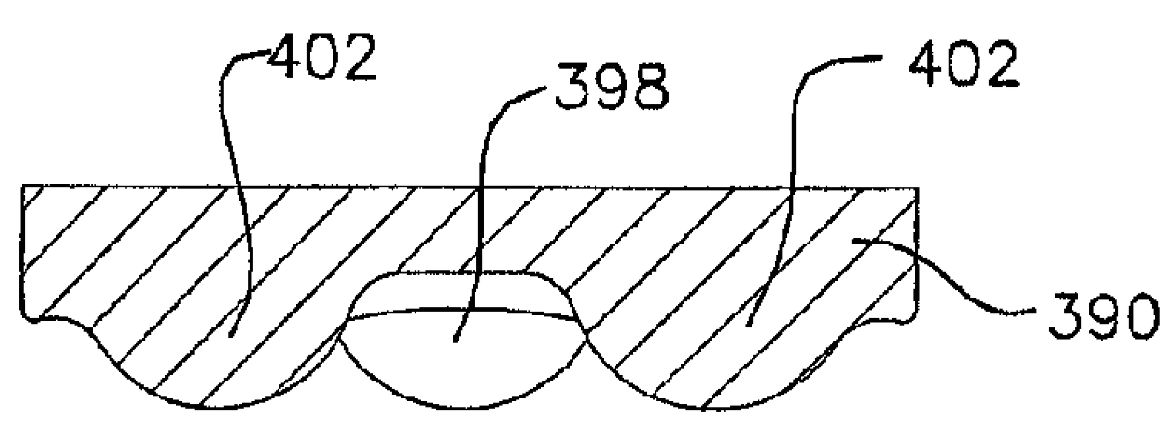

FIG. 46

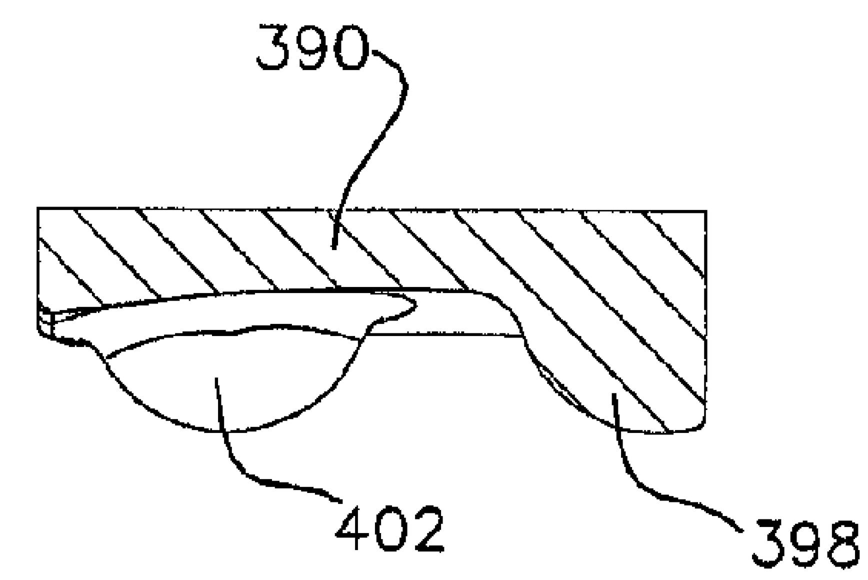

FIG. 44

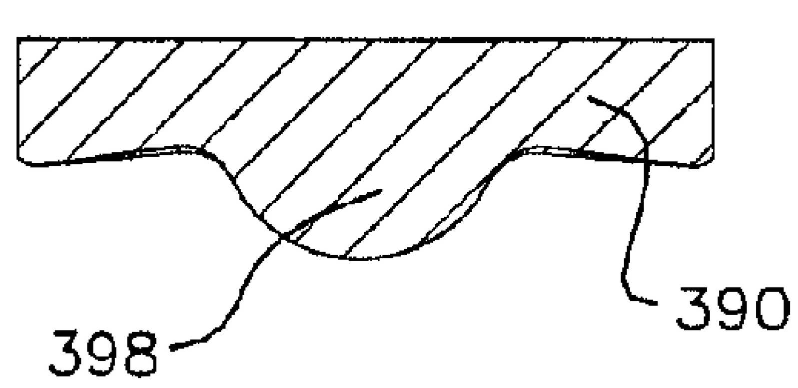

FIG. 47

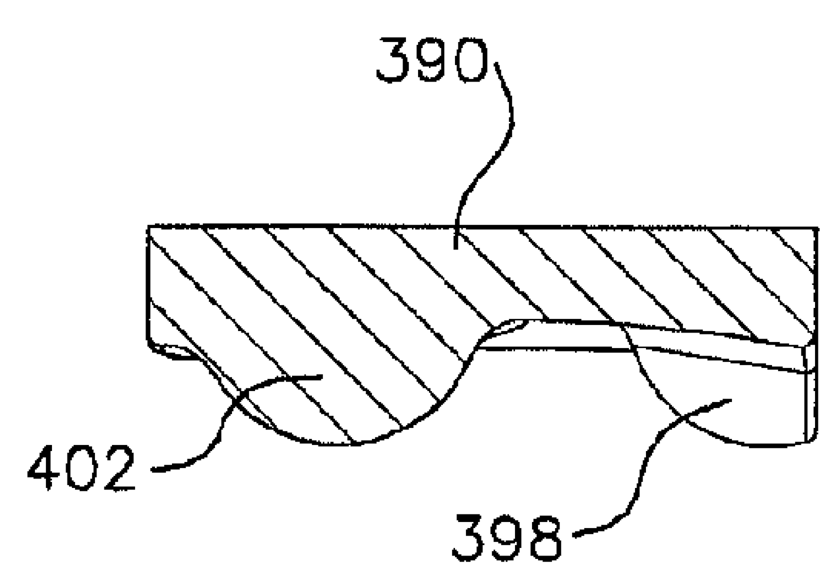

FIG. 45

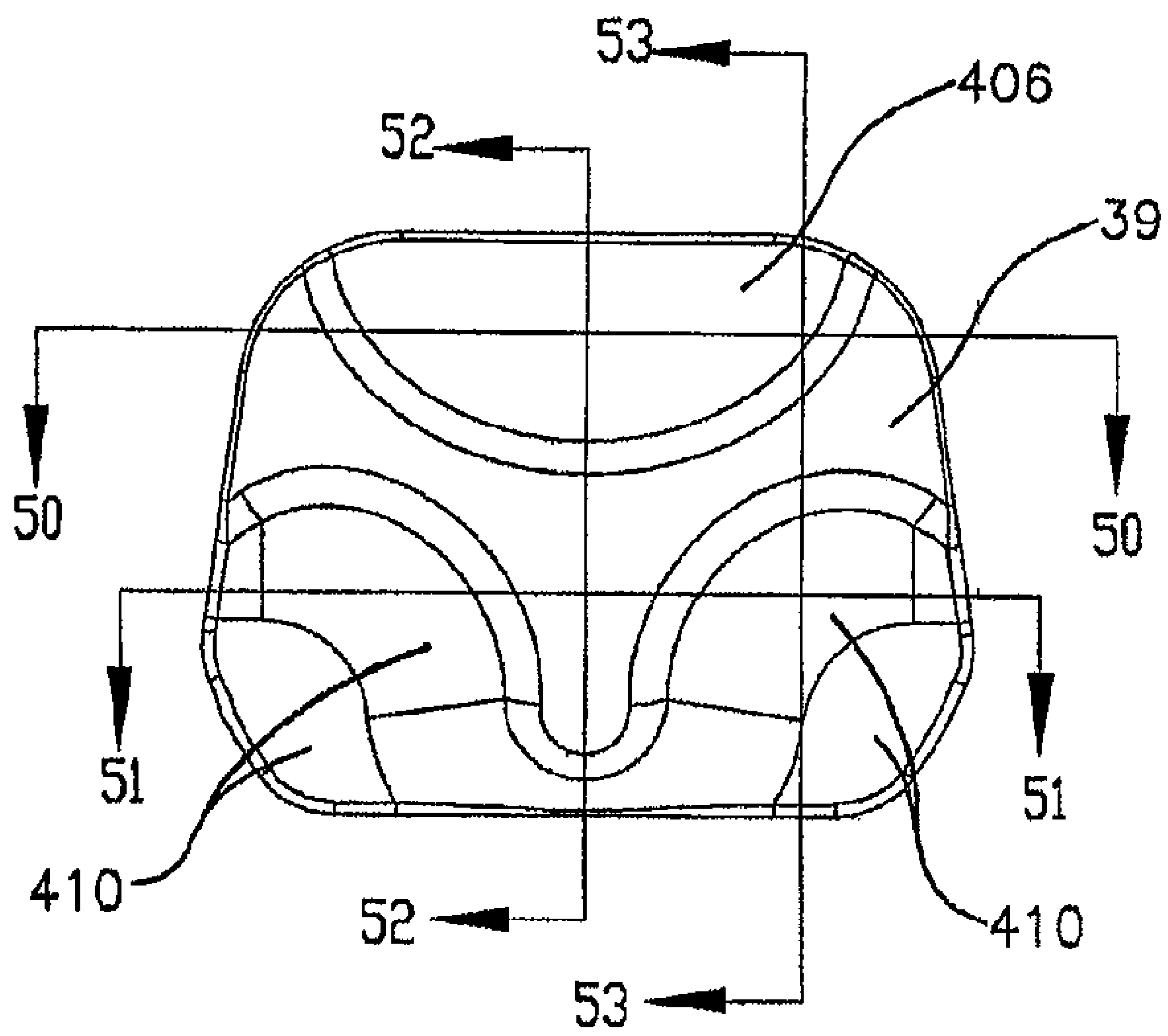

FIG. 49

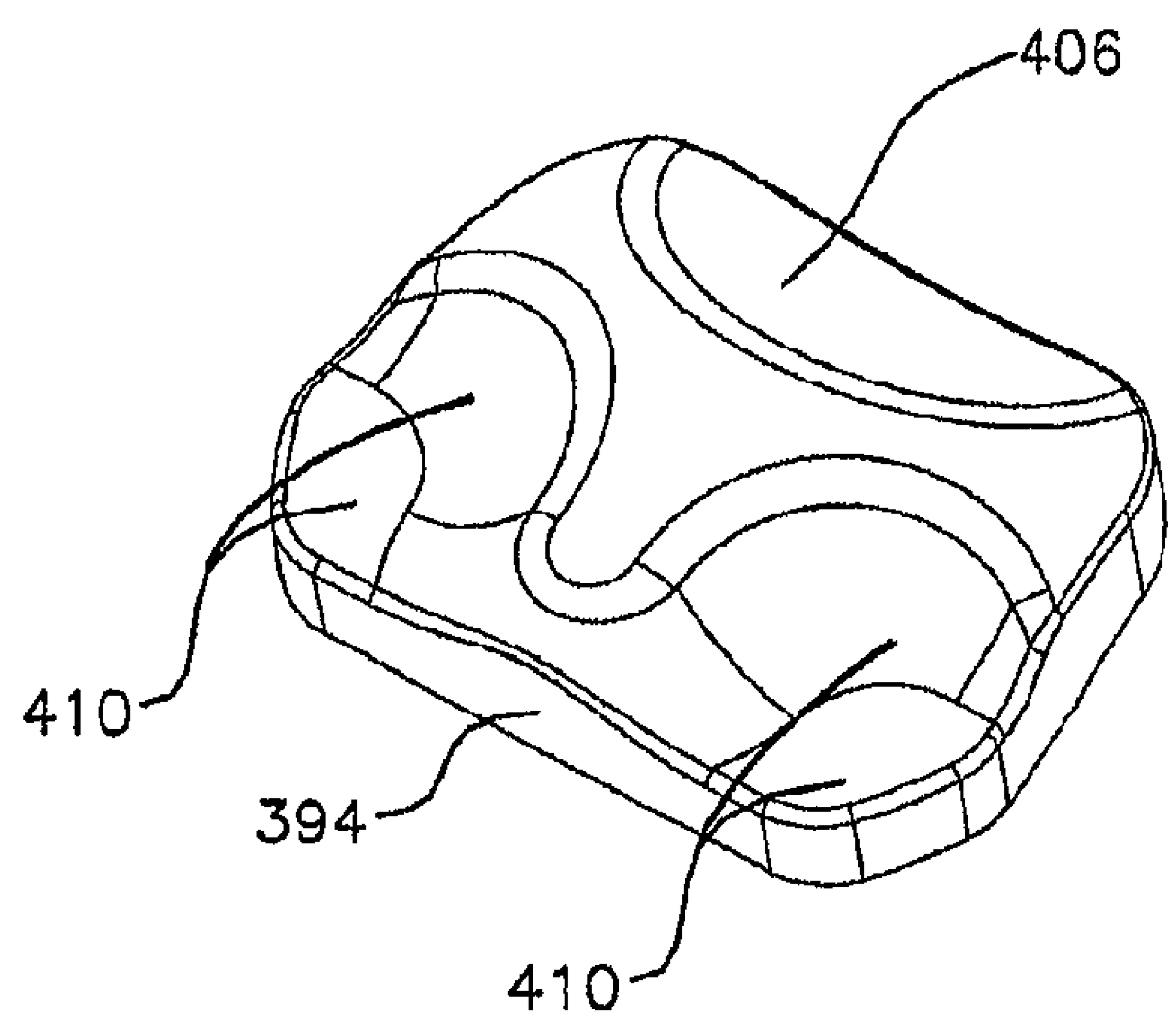

FIG. 48

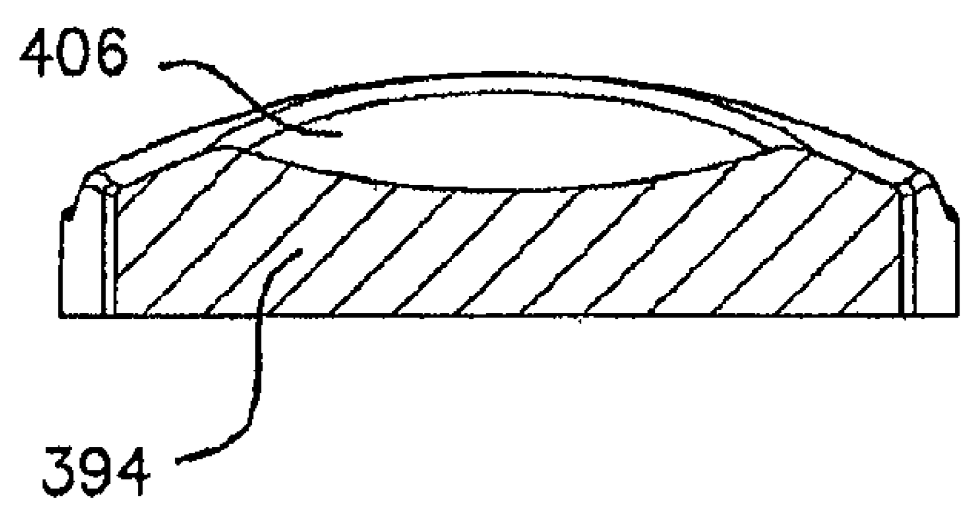

FIG. 50

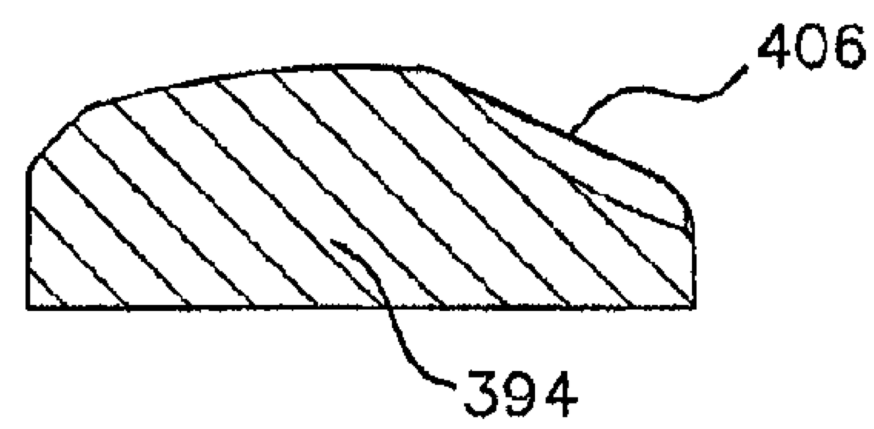

FIG. 52

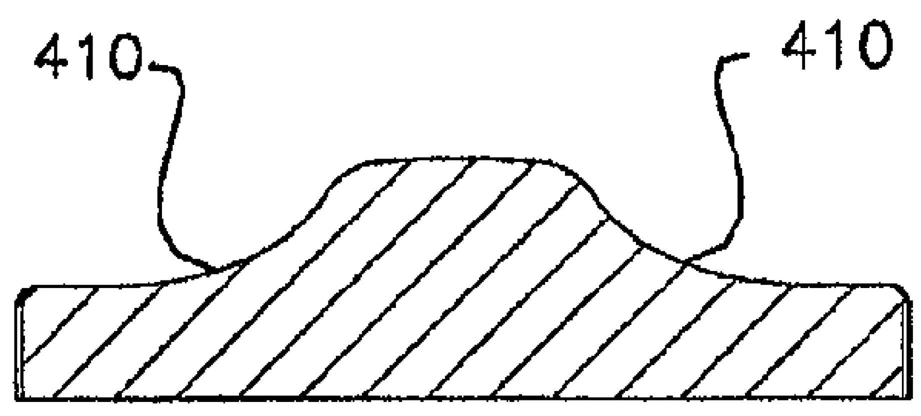

FIG. 51

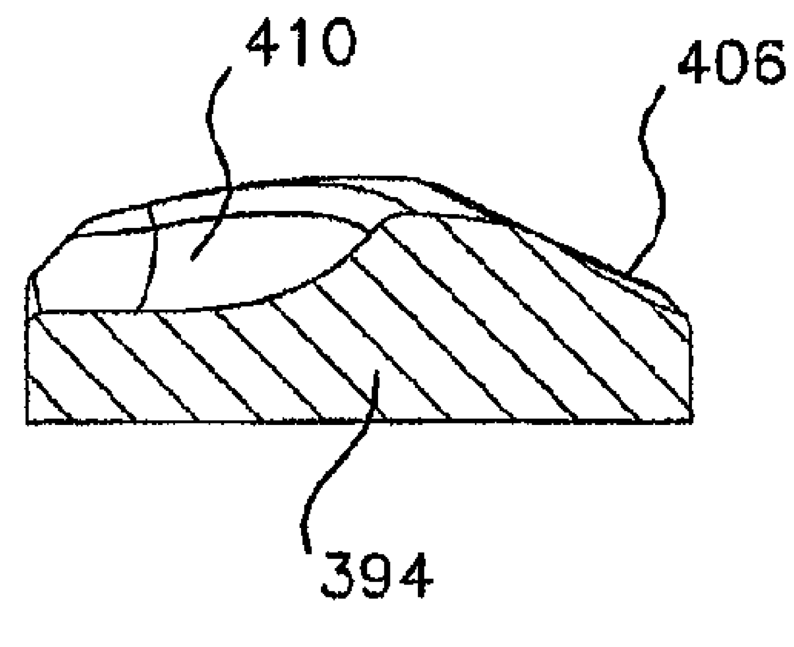

FIG. 53

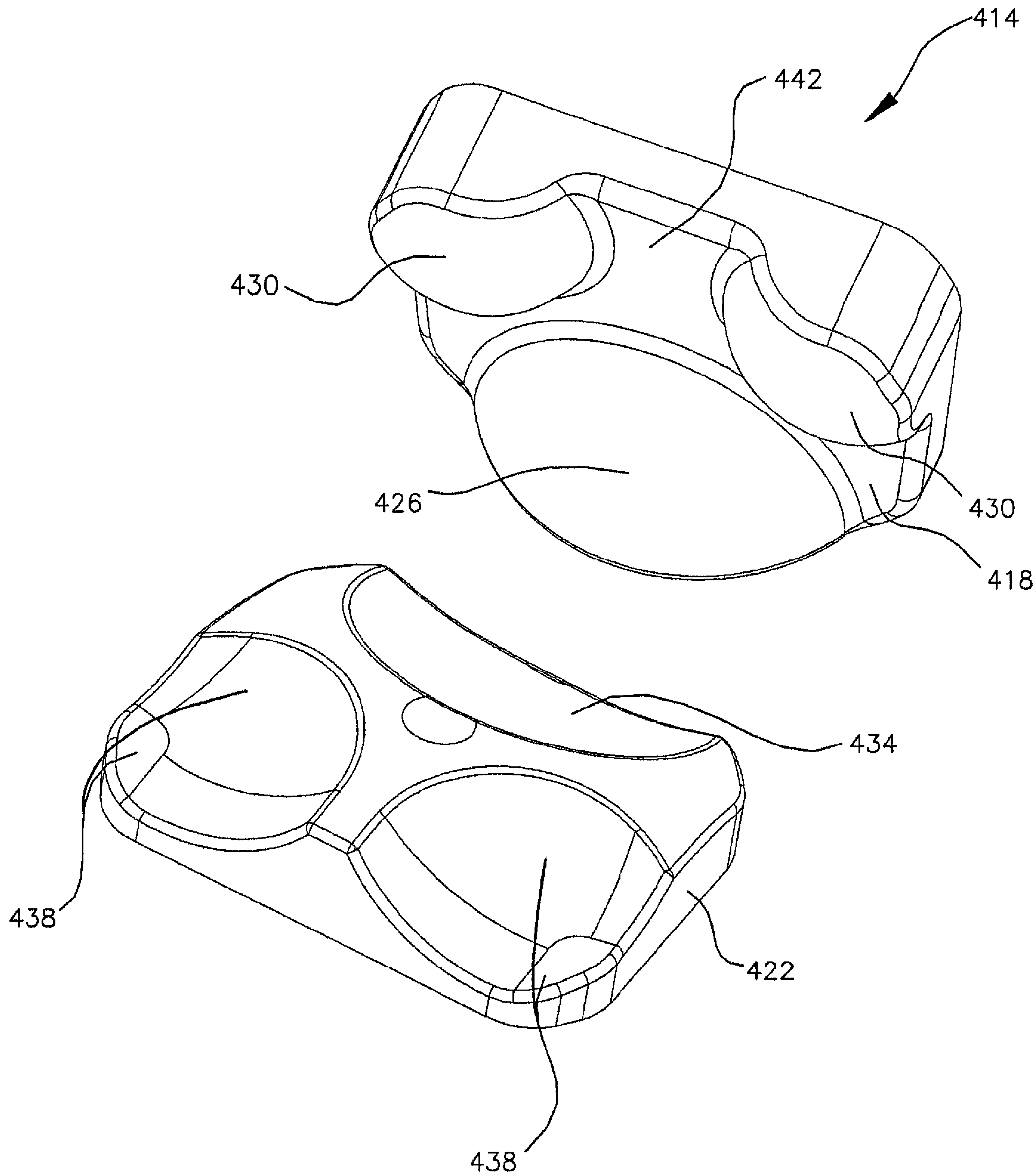

FIG. 54

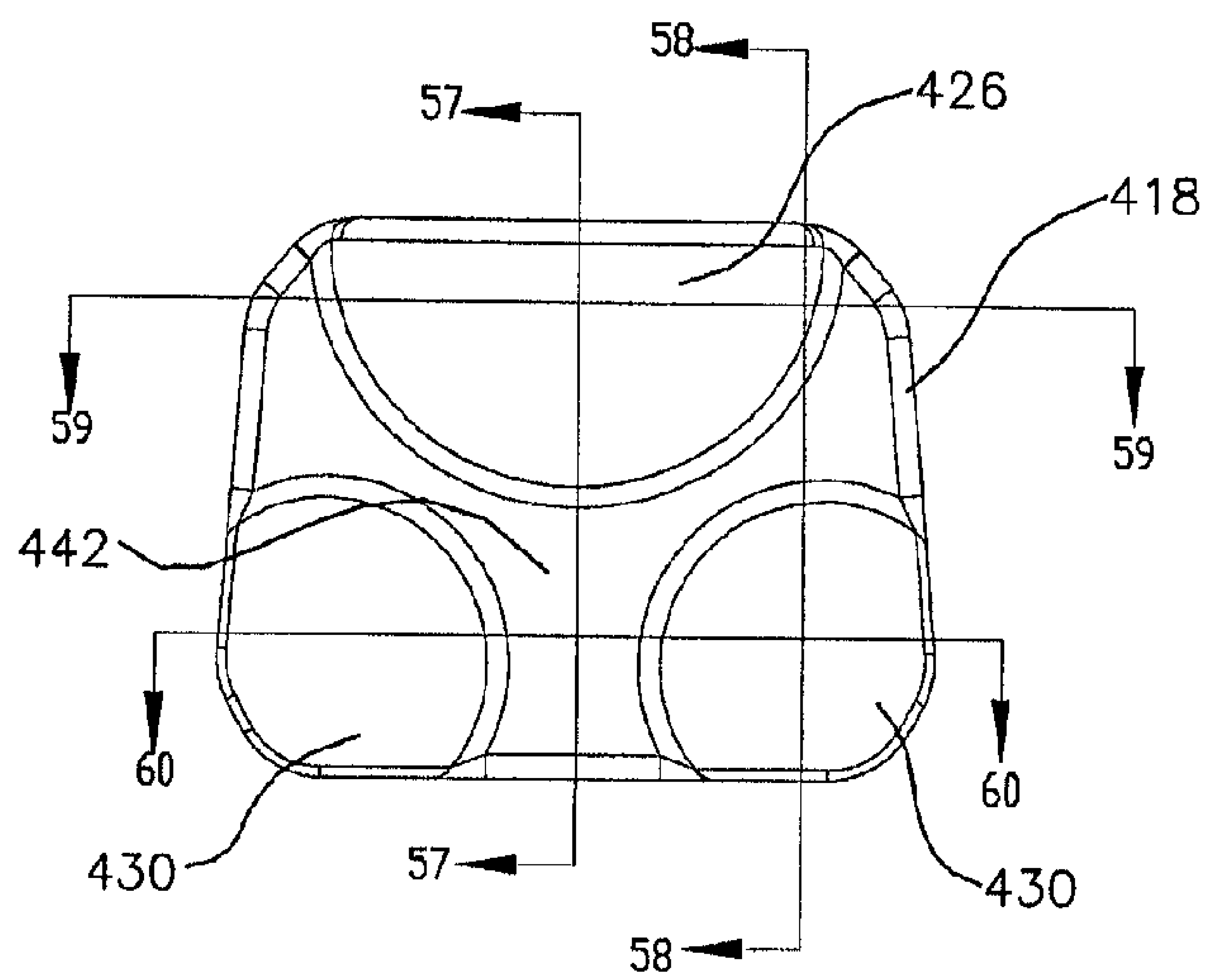

FIG. 56

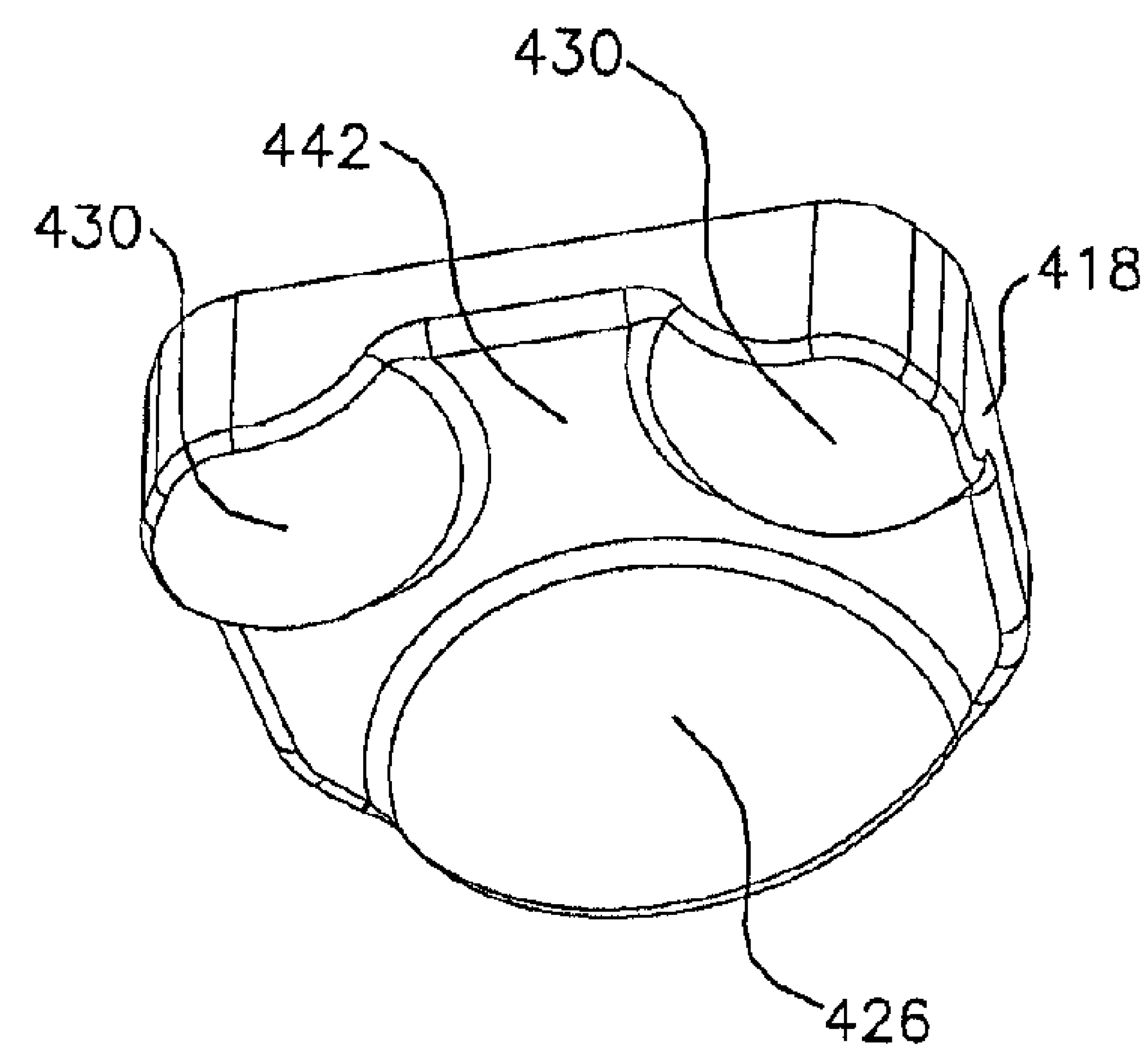

FIG. 55

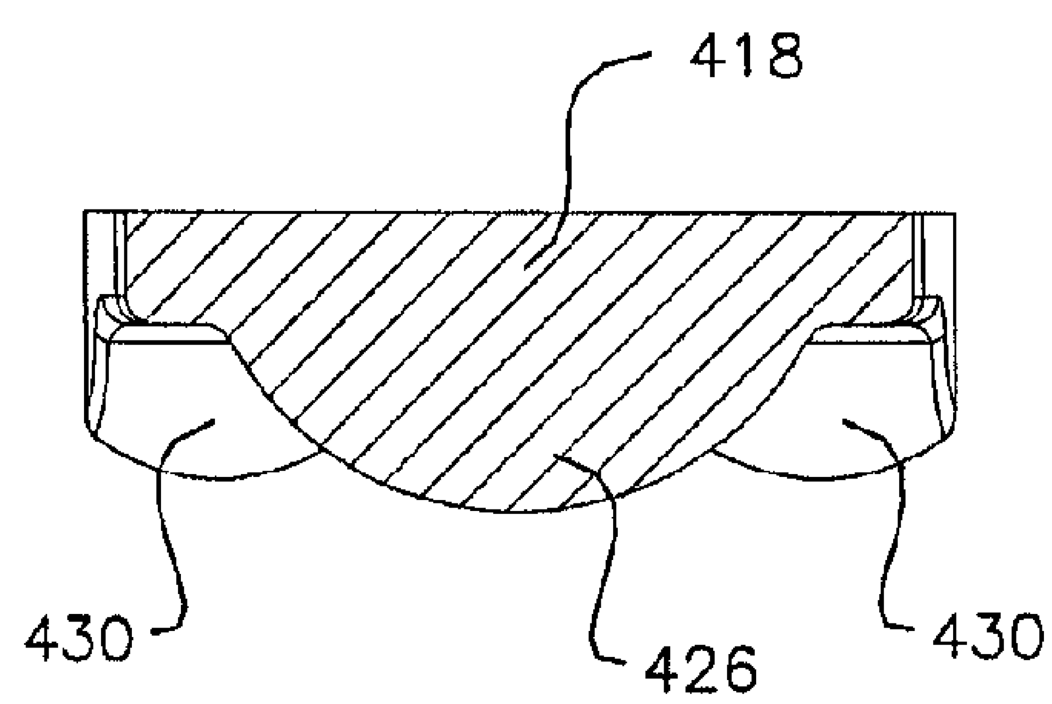

FIG. 59

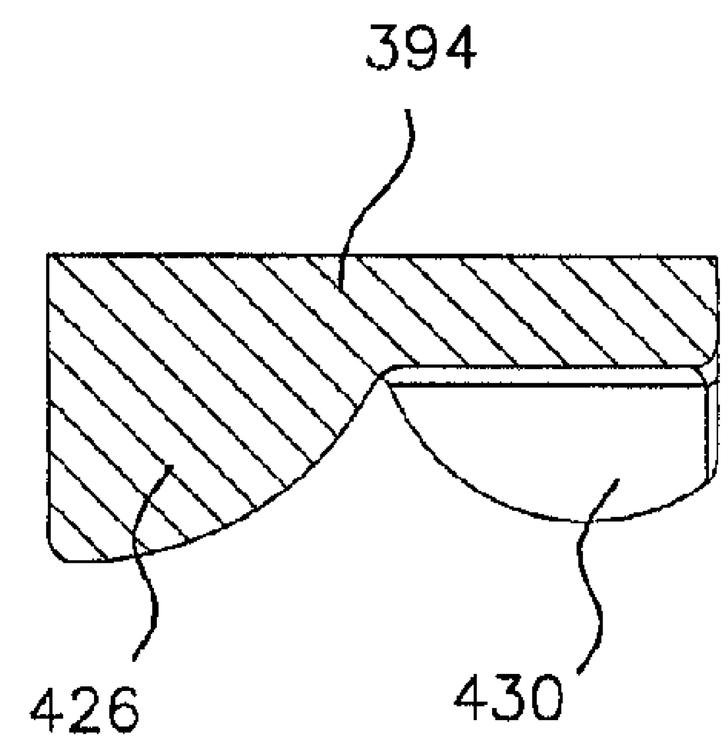

FIG. 57

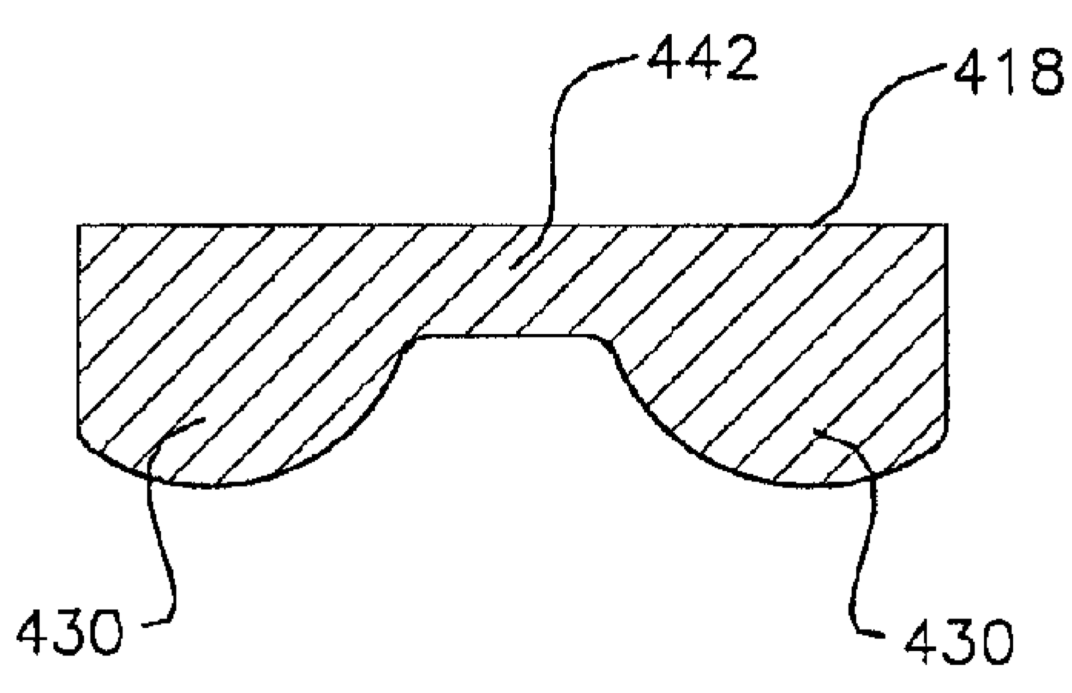

FIG. 60

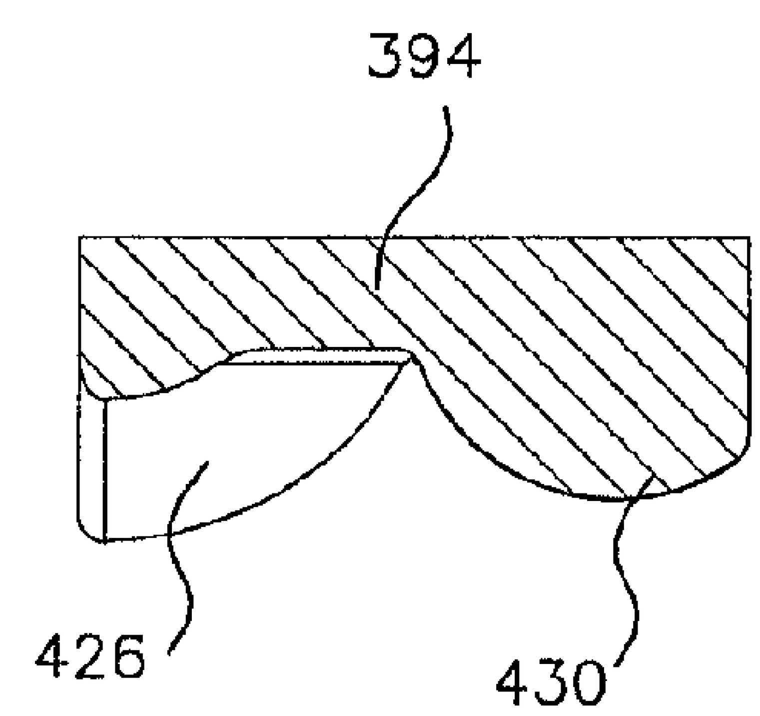

FIG. 58

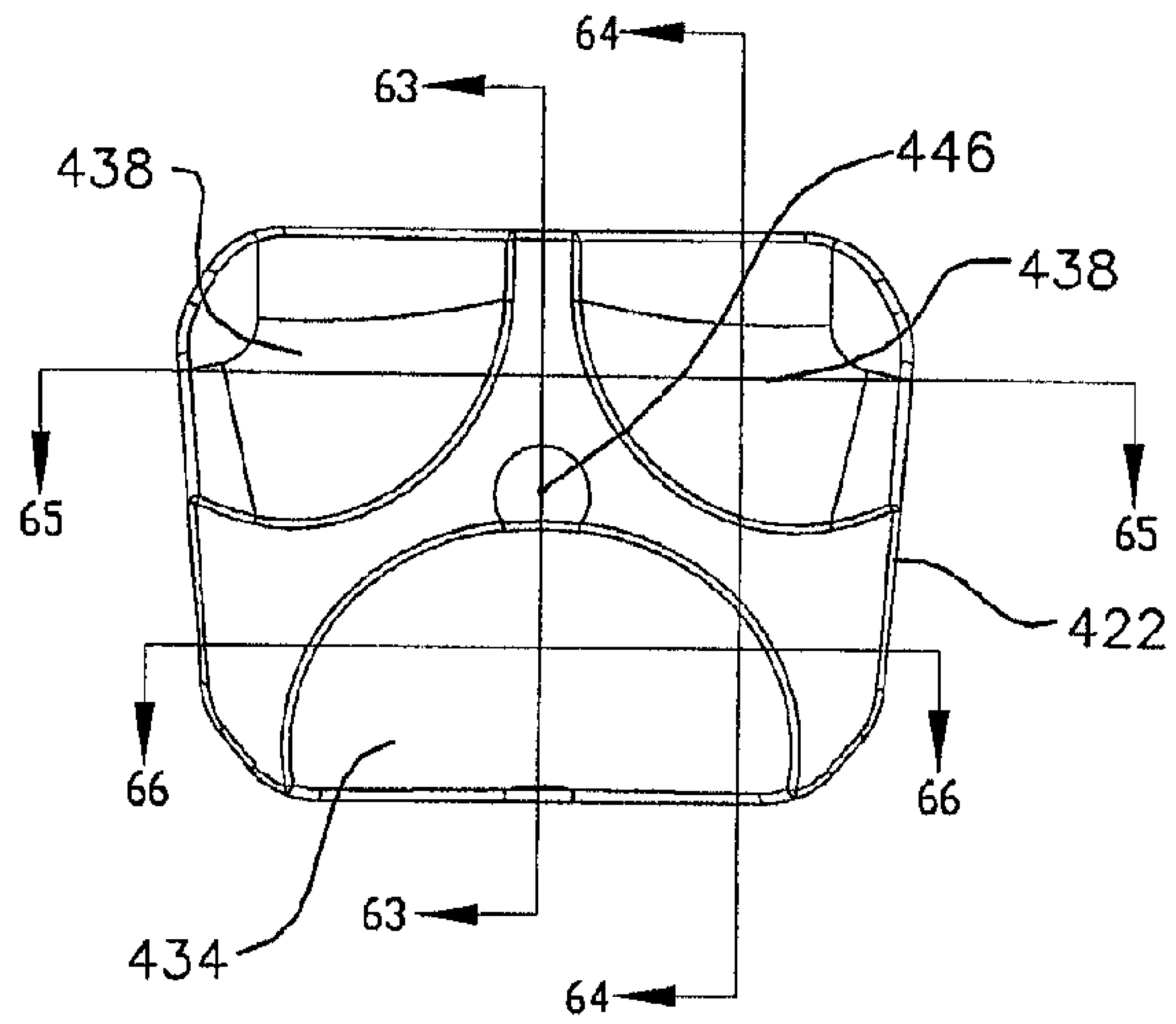

FIG. 62

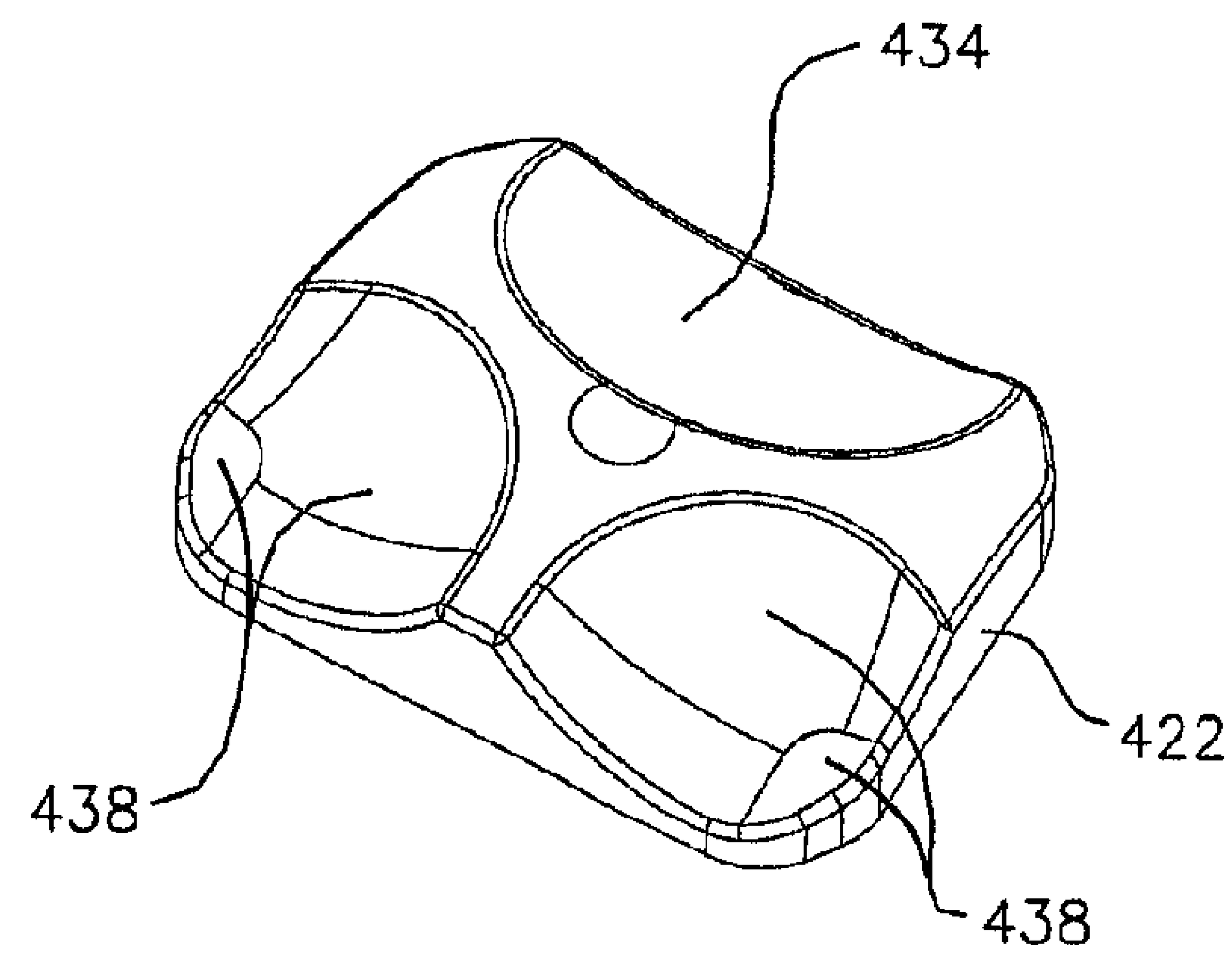

FIG. 61

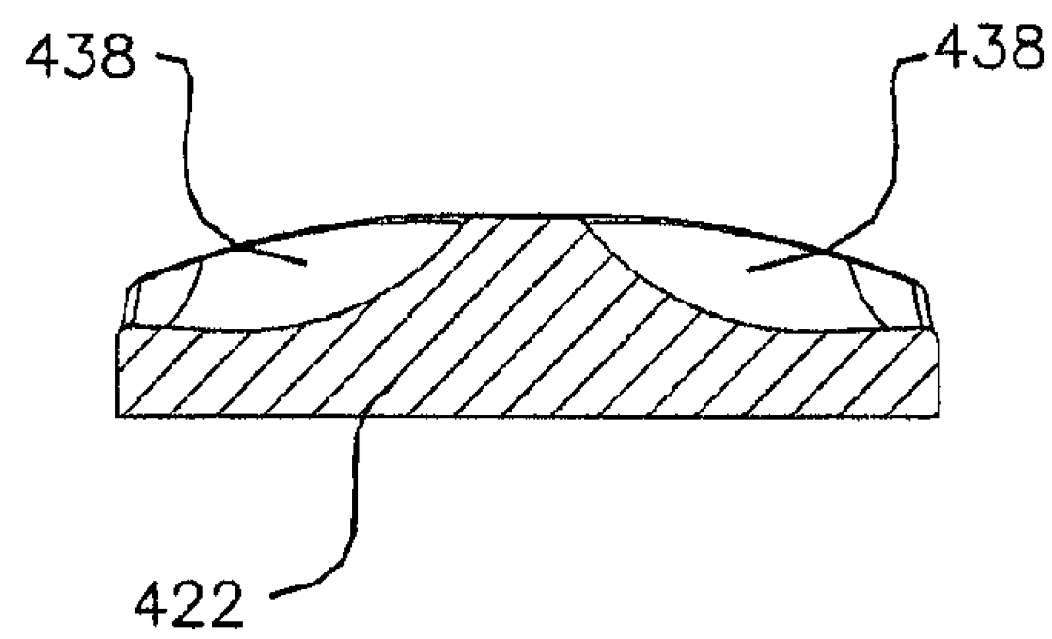

FIG. 65

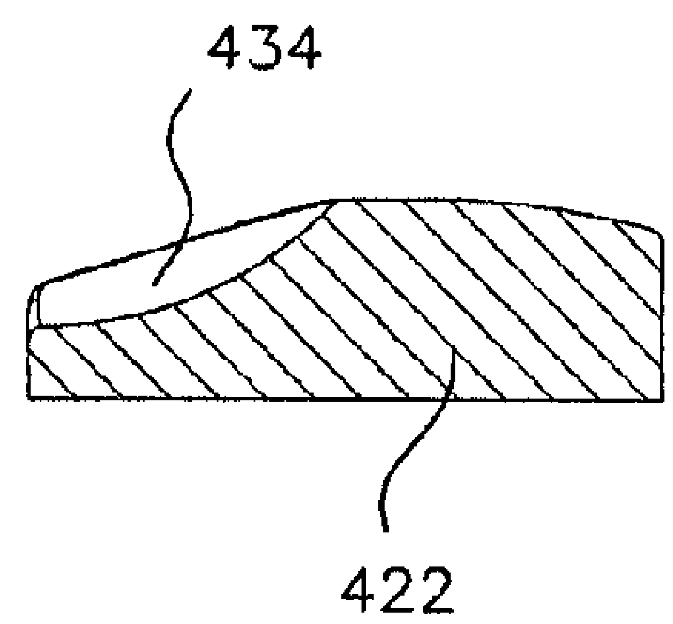

FIG. 63

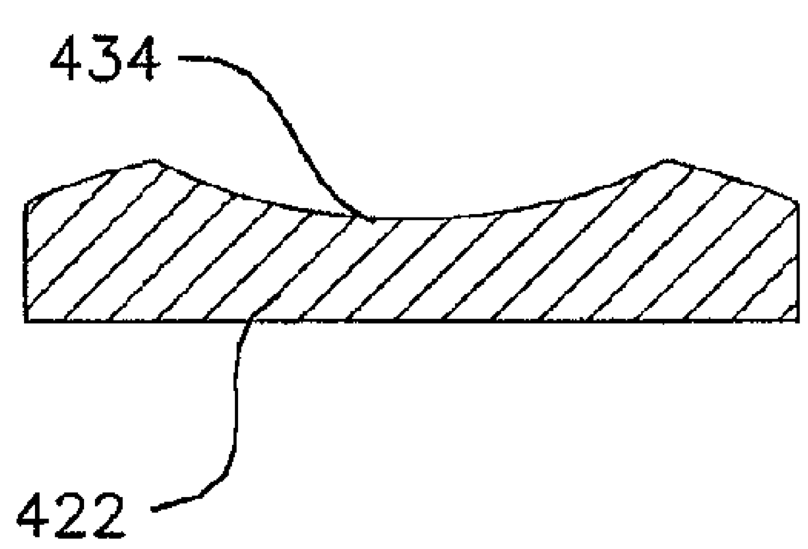

FIG. 66

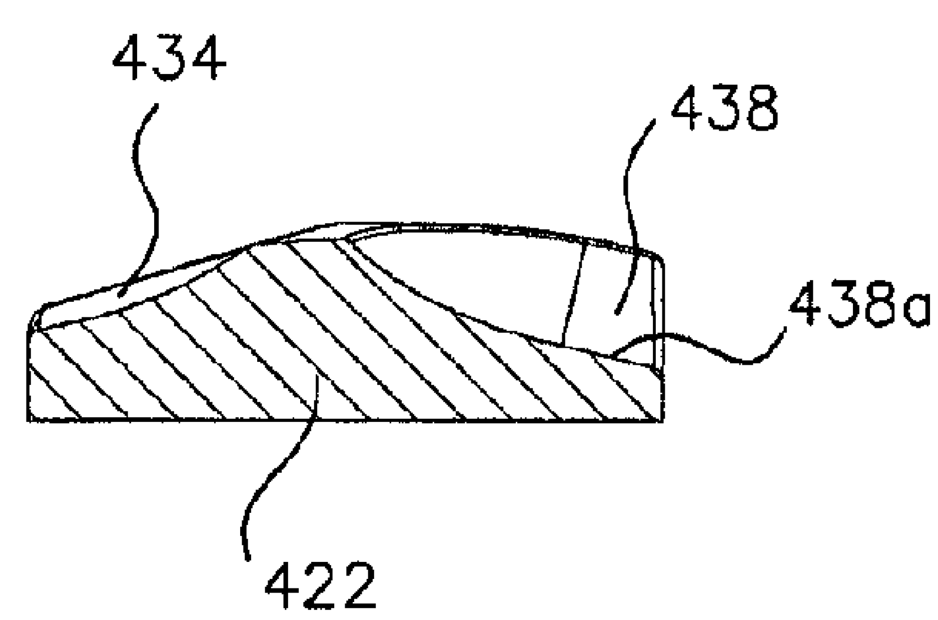

FIG. 64

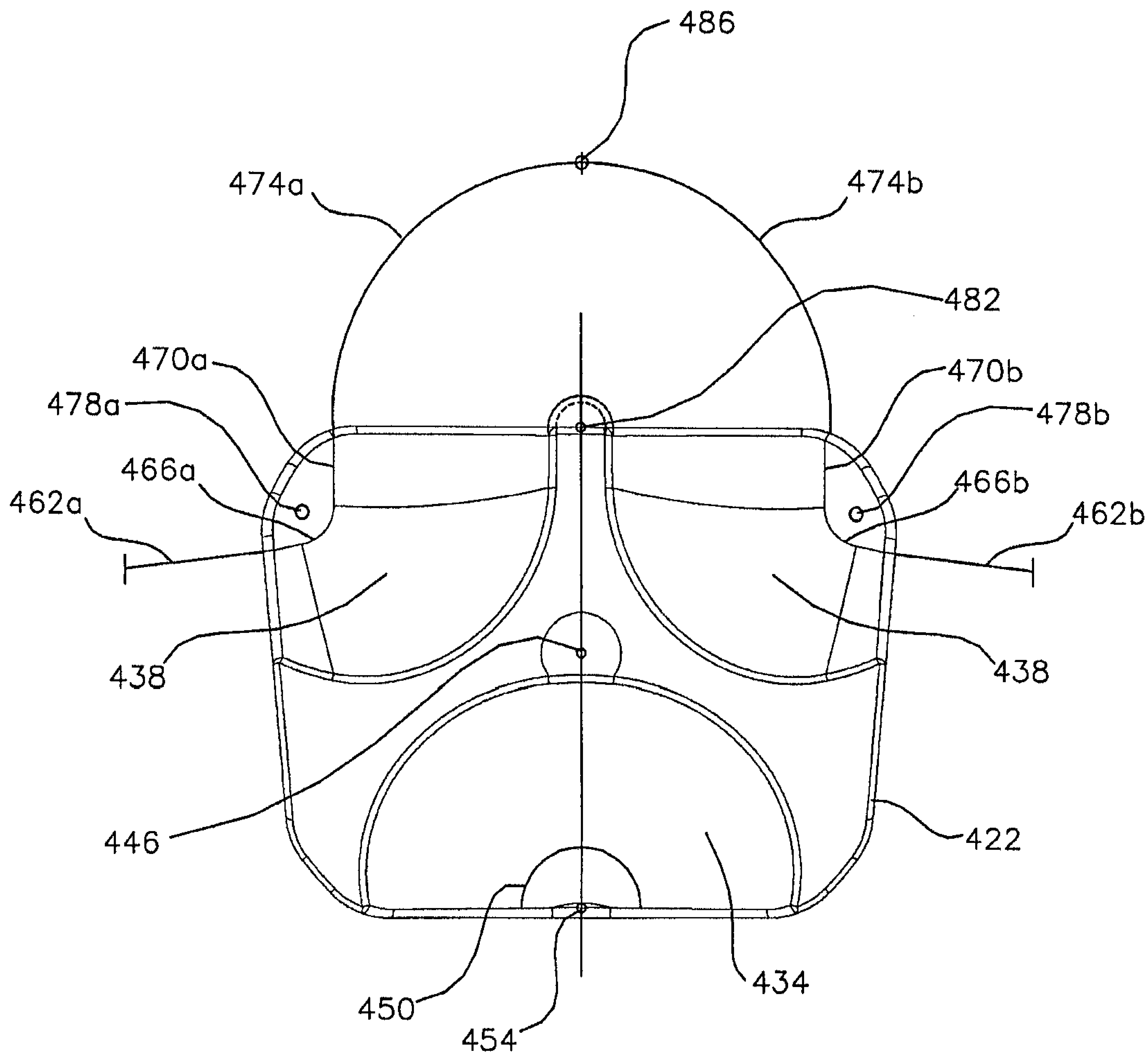
486
474a
474b
482
470a
470b
478a
478b
466a
466b
462a
462b
438
438
446
422
434
450
454

FIG. 67

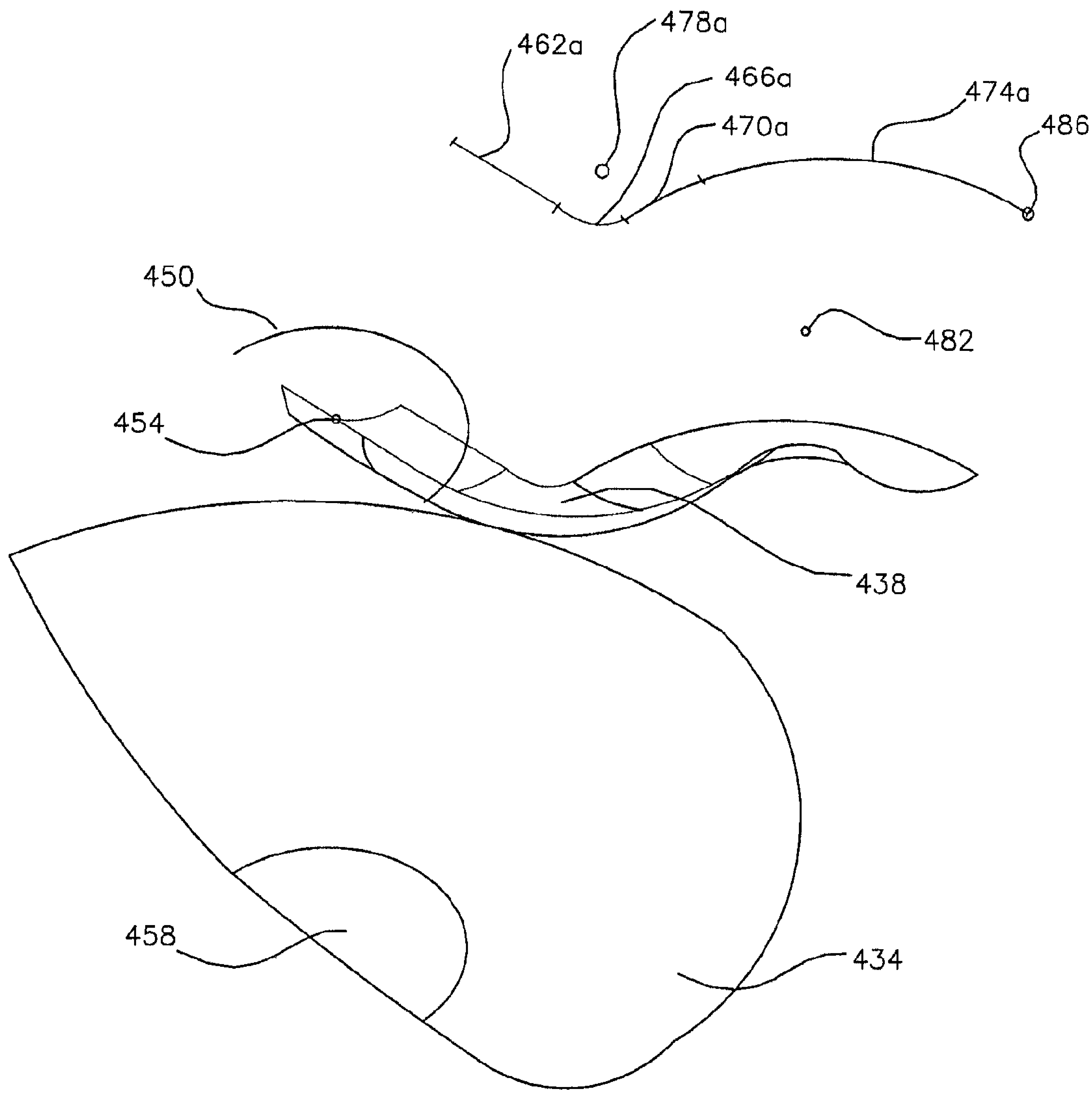

FIG. 68

MULTI-LOBE ARTIFICIAL SPINE JOINT

RELATED APPLICATIONS

The present application is a continuation application of U.S. patent application Ser. No. 13/445,833, filed Apr. 12, 2012, now U.S. Pat. No. 8,603,169, which is incorporated herein by reference in its entirety, and which is a continuation of U.S. patent application Ser. No. 12/028,740, filed Feb. 8, 2008, now U.S. Pat. No. 8,163,023, which is incorporated herein by reference in its entirety, and which claims the benefit of U.S. Provisional Application Ser. No. 60/889,217, filed Feb. 9, 2007, which is incorporated herein by reference in its entirety, and U.S. Provisional Patent Application Ser. No. 60/914,469, filed Apr. 27, 2007, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. The Field of the Invention

The present invention relates to artificial joints, and in particular to an artificial inter-vertebral disc for replacement of damaged spinal discs. The present invention relates to an improved artificial inter-vertebral disc for both total disc replacement and for nuclear replacement.

2. State of the Art

Artificial joints are increasingly becoming more common for the medical treatment of degenerated boney joints. Joints may become damaged due to accidents, diseases, aging, etc., and are often replaced when the pain is sufficient, or when natural motion of the joint is sufficiently impaired. Artificial joints commonly replace the tissue between adjoining bones, and may often replace the ends of the two adjoining bones which form the joint.

In replacing a joint, there are generally several desirable outcomes to be achieved. These outcomes include: stability, load bearing capability, natural motion preservation, pain relief, and reduced failure rates and reduction in catastrophic failure. Due to the complexity of the human spine, stability has been a very difficult parameter to address. Often this instability manifests itself as additional wear and premature failure of the artificial joint or supporting physiological structures, adjacent segment/joint degeneration, and exacerbating the pain and disability of the patient.

A number of artificial discs which are presently available tend to lack the stability of the natural spine. Many total disc replacement devices (TDR) are of the "ball in cup" or "ball in trough" design. One of the problems of these particular designs is that the TDR requires the surrounding tissues and structures (ligaments and joints) to provide support and stability. Due to the physical geometry of these designs, the further the spine is moved from the "neutral position" the more the artificial joint has a tendency to continue moving in that direction, thus applying unnatural stress on the surrounding tissues and structures and requiring greater forces to return the joint to the "neutral position." Over time, the constantly applied and increased loads required to operate the artificial joint may lead to damage to the muscles, connected tissues and adjacent structures of the spine, exacerbating the pain and hampering proper movement of the spine. It has also been discovered that, due to the instability of the replaced disc, the spine can develop scoliosis, or curvature, which tends to lead to additional deterioration of the tissues associated with the spine, such as failure of adjacent joints.

The neutral position for a joint is the normal resting position for the joint, and is typically in the middle of the range of

motion for a spinal joint. For a typical spine, two adjacent vertebral bodies have endplates which are approximately parallel in the neutral position.

Another parameter that must also be controlled is the ability to mimic the natural kinematic motion of the spine. Many joints in the human body can be adequately approximated by simple joints such as a hinge or a ball in socket. Because of the complex construct of the spinal joint, it cannot be approximated by simple joints. Many prior artificial discs allow the vertebrae to move in a pivotal motion having symmetrical movements. The differences in movement between a natural joint and an artificial joint can cause undesirable effects on the surrounding muscle and tissue. This can cause a degeneration and inability to properly move and control the artificial joint accentuating the instability of the artificial joint, and may accelerate further joint problems.

There is a need for an artificial joint that is more energetically stable with the inherent tendency to return the joint to a "neutral position" in order to reduce the stress and fatigue on the surrounding tissues and structures. Additionally, there is additional need for the artificial joint to more accurately match the natural kinematic motion of the spine to reduce stress and fatigue again on the surrounding tissues and structures. These are but two parameters important to designing a successful spinal disc replacement.

SUMMARY OF THE INVENTION

The objective of the present invention is to provide an improved artificial disc. One objective of the invention is to create an artificial disc that more closely matches the movement of the natural spine. To closely match the natural motion of the spine, one method would be to use non-congruent articulating surfaces that allow for asymmetrical and/or coupled movement. Such an artificial disc would promote long term success of the replaced joint as it maintains more natural motions of the muscles and tissues surrounding the joint. By more closely matching the natural movement, the artificial disc helps prevent degeneration of surrounding tissues and adjacent segment, while promoting better patient mobility of the joint.

A further objective of the present invention is to provide an artificial disc which is more energetically stable. When displaced from a neutral position, the compressive forces naturally applied to the spine such as from gravity and the tension in surrounding tissues urges the artificial joint back into a neutral position and not away from a neutral position. Such an artificial joint is especially beneficial where multiple discs are replaced as it avoids tissue fatigue and joint instability.

These and other aspects of the present invention may be realized in an artificial disc which uses a plurality of projections to engage a mating surface to allow naturally constrained translational and rotational movement between two adjacent vertebrae. The mating surface typically includes a plurality of recesses which receive the projections. The projections are able to slide within the recesses to provide both translational and rotational movement, i.e. flexion/extension, lateral bending, and axial rotation. The projections and recesses are preferably configured to provide coupled translational and rotational movement, causing tilting of a joint member as it slides across the mating joint member. One or more of the projections may also be able to rise partially out of the recess, typically by engaging a wall or sloping portion of the recess, thereby providing an energetically stable system.

Alternatively, other structures such as a single projection and recess having multiple engagement surfaces as described herein may provide the desired relative movement between the top and bottom of the artificial joint. Likewise, intermediate structures between the top and bottom of the artificial joint may be used to provide the desired motion and stability.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of the present invention are shown and described in reference to the numbered drawings wherein:

FIG. **1** shows a side view of an art artificial joint in accordance with principles of the prior art;

FIG. **2** shows a side view of a spine having multiple prior art artificial joints;

FIG. **3** shows a top view of a vertebra of a human;

FIG. **4** shows a schematic side view of two vertebrae illustrating the vertebral motion in forwards and backwards flexion/extension of the spine;

FIG. **5**A shows a schematic top view of a vertebra illustrating the vertebral motion in lateral bending of the spine;

FIG. **5**B shows a schematic side view of two vertebrae illustrating the vertebral motion in lateral bending of the spine;

FIG. **6**A shows a schematic top view of a vertebra illustrating the vertebral motion during rotation of the spine;

FIG. **6**B shows a schematic side view of two vertebra illustrating the vertebral motion in rotation of the spine;

FIGS. **7**A and **7**B show the motion of the prior art artificial joint of FIG. **1** in flexion and rotation;

FIG. **8** shows a disassembled perspective view of an artificial disc of the present invention;

FIG. **9** shows a partially cut-away top view of an artificial disc of the present invention taken along line **9-9** of FIG. **8**;

FIG. **10** shows a side view of the base portion of the artificial disc of FIG. **9**;

FIG. **11** shows a top view of a base portion and a cross-sectional view of the projections of an artificial disc of the present invention;

FIG. **12** shows a top view of a base portion and a cross-sectional view of the projections of an artificial disc of the present invention;

FIG. **13**A shows a cross-sectional view of the artificial discs of FIGS. **8** through **12** taken along line **13-13** of FIG. **12**;

FIG. **13**B shows another cross-sectional view of the artificial disc of **13**A, with the projections having been moved in the troughs to thereby change the angle of the upper portion of the artificial disc;

FIG. **13**C shows another cross-sectional view of an artificial disc of the present invention;

FIG. **14**A shows a cross-sectional view of the artificial discs of FIGS. **8** through **12** taken along line **14-14** of FIG. **12**;

FIG. **14**B shows another cross-sectional view of the artificial disc of FIG. **14**A, with the projection having been moved in the trough to thereby change the angle of the upper portion of the artificial disc;

FIG. **15** shows a cross-sectional view of the artificial discs of FIGS. **8** through **12** taken along line **15-15** of FIG. **12**;

FIG. **16** shows a close-up cross-sectional view of a projection and trough of the artificial disc of the present invention;

FIG. **17** shows another detailed cross-sectional view of a projection and trough of the artificial disc of the present invention;

FIG. **18** shows another top view of the lower portion and projections of the upper portion of an artificial disc of the present invention;

FIG. **19** shows another top view of an artificial disc of the present invention;

FIG. **20** shows a cross-sectional view of the artificial disc of FIG. **19** taken along line **20-20**;

FIG. **21** shows a perspective view of an artificial joint of the present invention having differently shaped projections;

FIG. **22** shows a cross-sectional view of the artificial joint of FIG. **21** taken along line **22-22** of FIG. **21**;

FIG. **23** shows a perspective view of another artificial joint of the present invention;

FIG. **24** shows a cross-sectional view of the artificial joint of FIG. **23** taken along line **24-24** of FIG. **23**;

FIG. **25** illustrates another artificial joint of the present invention;

FIG. **26** shows an artificial joint of the present invention used as a disc nucleus replacement;

FIG. **27** shows an artificial joint having a restraining band according to the present invention;

FIG. **28** shows a cross-sectional view of another artificial joint of the present invention;

FIG. **29** shows another cross-sectional view of the joint of FIG. **28**;

FIG. **30** shows an exploded perspective view of a artificial joint similar to that of FIGS. **8-18**;

FIG. **31** shows a bottom view of the upper portion of the joint of FIG. **30**;

FIGS. **32** and **33** show cross sectional views of the upper portion of the joint of FIG. **30** taken along section lines **32** and **33** of FIG. **31**;

FIG. **34** shows a bottom perspective view of the upper portion of the joint of FIG. **30**;

FIG. **35** shows a top view of the lower portion of the joint of FIG. **30**;

FIG. **36** through **39** show cross sectional views of the lower portion of the joint of FIG. **30** taken along section lines **36** through **39** of FIG. **35**;

FIG. **40** shows a perspective view of the lower portion of the joint of FIG. **30**;

FIG. **41** shows an exploded perspective view of an artificial joint similar to that of FIGS. **8-18**, and **30-40**;

FIG. **42** shows a bottom perspective view of the upper portion of the joint of FIG. **41**;

FIG. **43** shows a bottom view of the upper portion of the joint of FIG. **41**;

FIG. **44** through **47** show cross sectional views of the upper portion of the joint of FIG. **41** taken along section lines **44** through **47** of FIG. **43**;

FIG. **48** shows a perspective view of the lower portion of the joint of FIG. **41**;

FIG. **49** shows a top view of the lower portion of the joint of FIG. **41**;

FIG. **50** through **53** show cross sectional views of the lower portion of the joint of FIG. **41** taken along section lines **50** through **53** of FIG. **49**;

FIG. **54** shows an exploded perspective view of an artificial joint similar to that of FIGS. **8-18**, **30-40**, and **41-53**;

FIG. **55** shows a bottom perspective view of the upper portion of the joint of FIG. **54**;

FIG. **56** shows a bottom view of the upper portion of the joint of FIG. **54**;

FIG. **57** through **60** show cross sectional views of the upper portion of the joint of FIG. **54** taken along section lines **57** through **60** of FIG. **56**;

FIG. **61** shows a perspective view of the lower portion of the joint of FIG. **54**;

FIG. **62** shows a top view of the lower portion of the joint of FIG. **54**;

FIG. **63** through **66** show cross sectional views of the lower portion of the joint of FIG. **54** taken along section lines **63** through **66** of FIG. **62**;

FIG. **67** shows a top view of the lower portion of the joint of FIG. **54** along with the tool path lines for forming the recesses; and

FIG. **68** shows a perspective view of the tool path lines, surfaces formed by the tool and recesses of FIG. **67**.

It will be appreciated that the drawings are illustrative and not limiting of the scope of the invention which is defined by the appended claims. The embodiments shown accomplish various aspects and objects of the invention, and any single figure need not accomplish each aspect or advantage of the invention. It is appreciated that it is not possible to clearly show each element and aspect of the invention in a single figure, and as such, multiple figures are presented to separately illustrate the various details of the invention in greater clarity.

DETAILED DESCRIPTION

The invention will now be discussed in reference to the drawings and the numerals provided therein so as to enable one skilled in the art to practice the present invention. The drawings and descriptions are exemplary of various aspects of the invention and are not intended to narrow the scope of the appended claims. In some figures, space is shown between adjacent structures which are normally in contact with each other in order to more clearly show the structures.

Currently, a number of artificial discs are presently available or being tested. These tend to lack the stability of the natural spine. These prior art joints typically include a bearing surface which includes a cup shaped receptacle on top of a spherical surface or a ball or spherical surface **10** placed in a cup shaped receptacle **14**, as shown in FIG. **1**. These joints move by pivoting in a manner similar to other known ball and socket joints. Rectangle **18** generally indicates body mass above the joint (as is supported by the particular joint), such as additional vertebrae, bones, and tissue. Circle **22** indicates a piece of the body weight above the joint, providing a reference point for illustrative purposes. As the ball **10** pivots into position **10'**, as would occur with the bending of the joint (where the person having the artificial joint is bending), body mass **18** and reference point **22** move to the locations indicated by **18'** and **22'**. It is appreciated that the position **22'** is at a lower vertical height that position **22**.

It is thus appreciated that as the joint pivots by rotating ball **10**, there is a general lowering of point **22** as it is moved to position **22'**. The pivoting of the joint is favored by gravity, as the body mass **18**, **22** above the joint is moved into a lower position. Gravity alone will apply a force to continue the movement, moving the body mass **18**, **22** into an even lower position. Additional force is required to move the body mass **18**, **22** back into its original position. The spine is in a state of compression due to the force of gravity acting on body mass above each joint and due to the tension of the muscles and other tissues surrounding each joint. These compressive forces tend to move the prior art artificial joints away from a neutral position, as the end points of motion represent minimum energy states, i.e. positions where the gravitational potential energy and tensile forces are minimized.

Thus, it is appreciated that the joint shown is a joint which is inherently unstable. Once moved off of a neutral position, compression on the joint as caused by the tension in surrounding tissue or the weight of the body above the joint tends to continue the movement. The prior art joint is stable at the end points of motion rather than in the middle position, meaning that compressive forces on the joint tend to move the joint to the end points of motion rather than to a center position.

The muscular structure and other tissue structures surrounding the prior art joint must hold the joint in a neutral position (i.e. a resting position where the joint is not displaced, where surrounding muscles and tissue are at resting length) against the compressive forces acting upon the spine, such as the force of gravity. As the spinal joints are seldom in a precisely neutral position, the surrounding muscles and tissues may undergo a considerable amount of stress in attempting to hold such an artificial joint in a desired position, such as when the person is sitting or standing vertically. Additionally, the surrounding muscles and tissues must work harder to return the joint to the neutral position after the bending of the spine. This, in turn, can lead to damage to the muscles, connected tissues and adjacent joints/structures of the spine, exacerbating the pain and hampering proper movement of the spine.

It can thus be understood how it is desirable to have an artificial disc which is energetically stable. It is desirable to have an artificial joint where the compressive forces acting on the spine such as the force of gravity acting on the body mass and weight above the joint tend to move the joint back to a neutral position and not away from a neutral position.

FIG. **2** shows an example of a person's spine which has two or more of the artificial discs of FIG. **1**. A plurality of vertebrae **30***a*-**30***g* and healthy vertebral discs **34***a*, **34***b*, **34***e*, **34***f* are shown. The natural vertebral discs between vertebrae **30***c* and **30***d*, and between vertebrae **30***d* and **30***e* have been replaced by prior art artificial discs **38***c* and **38***d*, including ball and trough discs as discussed with respect to FIG. **1**. As has been discussed, ball and trough discs present inherent instability, where compressive forces such as gravity accentuate movement and pull the joint farther from a neutral position instead of returning the joint to a neutral position.

The problem is increasingly severe with two or more artificial discs as is shown with **38***c* and **38***d*. When one artificial disc, such as **38***d*, is moved from a neutral position, the forces of gravity, unbalanced tension of the body tissues surrounding the spine, etc. cause the second artificial disc **38***c* to pivot in the opposite direction of **38***d*. A patient having multiple prior art artificial discs may not be able to maintain their spine in a proper alignment or posture as the artificial discs tend to urge the spine into a bent or collapsed position. Thus, the spine either develops a scoliosis, or curvature, due to the instability of the artificial discs **38***c*, **38***d*, and the inability of the body to hold the spine in a proper position, or significantly more stress is placed on the muscles and connective tissue in order for the body to hold the spine in its proper orientation. Over time, the bending or collapsing of the spine due to the artificial discs tends to deteriorate the tissues associated with the spine. It is thus appreciated that where an artificial disc lacks a natural stability, the long term success of the artificial joint is reduced, and is dramatically reduced with increasing numbers of discs being replaced. In fact, the artificial joint may accelerate the failure of otherwise healthy spinal components.

A spine having a single prior art artificial disc may result in a undesired and excessive bending of one or more adjacent natural discs, resulting in a spinal shape similar to that shown in FIG. **2**. The undesired bending of the natural discs adjacent to the artificial joint may cause or accelerate degradation of the natural joints, and may result in the need to replace additional discs.

A further concern of an artificial disc is the preservation and restoration of a natural motion. Providing natural motion with an artificial joint is important for multiple reasons, such as providing comfortable movement to the person. Perhaps more important is the effect the artificial joint can have on the surrounding tissue. If the motion is unnatural, the tissues responsible for moving the joint, such as the surrounding muscles, tendons, etc. may be adversely affected by the joint. The surrounding tissue may be unable to properly control the joint, or may gradually degenerate due to the changed movement of the artificial joint. Thus, providing an artificial joint with a natural motion can have a significant effect on the long term success of an artificial joint.

Many artificial joints, such as artificial knees or hips, are relatively simple joints with relatively simple motion, such as hinge or ball in socket type joints. Vertebrae and the natural discs, however, have a complex motion. The natural discs are a soft pad, not unlike a mattress. The natural discs allow for and support the movement of the vertebrae, and allow the vertebrae to shift across the disc with combinations of horizontal, vertical and rotational movement to accomplish the normal movements of the spine.

Prior art artificial discs such as that shown in FIGS. **1** and **2** do not match the natural movement of the spine well. Many prior art artificial discs allow the vertebrae to move in a pivotal motion, and have symmetrical forwards and backwards movement. As has been mentioned, the differences in movement between a natural joint and an artificial joint can cause undesirable effects on the surrounding muscle and tissue. The muscle and tissue are oriented and accustomed to move the joint in a natural motion, and may degenerate or be unable to properly control the artificial joint having an unnatural motion. This degeneration and inability to properly move and control the artificial joint accentuates the instability of the prior art artificial joint, and may cause or accentuate the joint problems discussed with respect to FIGS. **1** and **2**.

It can thus be appreciated how it is desirable to have an artificial disc which results in a joint which is energetically stable and which provides a natural motion. Achieving such results provides an artificial disc and resulting joint which minimizes adverse effects on the body such as degradation of the surrounding tissues responsible for controlling the joint and the failure of the joint to provide support to the body in a natural position.

A study of the movement of the cervical spine (the neck) reveals that the kinematic motion of the spine is a complex and asymmetrical movement. The movement of the spine is observed to be a coupling of translational and rotational motion of the vertebral bodies. Herein, the motion of the spine is typically described by describing the motion of the portion of the vertebral body above the relevant spinal disc relative to the corresponding portion of the vertebral body below the disc. Flexion/extension involves the translation of the vertebral body forwards or backwards in combination with rotation of the vertebral body in the same direction of translation. Rotation typically involves rotation of the vertebral body about a point somewhat behind the center of the vertebral body in combination with some lifting and some sideways tilting, the vertebral body tilting to the left somewhat during a left rotation, etc. Lateral bending (side to side) is accomplished by cooperation of multiple vertebral joints in a combination of rotation, flexion/extension, and lateral tilting. The motion of the natural spine has been described by: Panjabi et al, Spine. 2001 Dec. 15; 26(24):2692-700; Ishii et al., Spine. 2006 Jan. 15; 31(2):155-60; Ishii et al, Spine. 2004 Dec. 15; 29(24):2826-31; and Ishii et al, Spine. 2004 Apr. 1; 29(7): E139-44.

FIG. **3** shows a top view of a vertebra **50**. The vertebra includes various structures for the attachment of surrounding tissue, the passage of the spinal column, etc. As the present invention concerns the vertebral discs and providing an artificial disc, the drawings and discussion of the vertebra will typically be limited to the vertebral body, the rounded frontal area indicated at **50*a*** which connects to the vertebral disc. Thus, the present application shows the vertebral bodies as rounded or cylindrical sections for simplicity. The posterior (back) of the disc area of the vertebra is indicated at point **54**, and the anterior (front) is indicated at **58**. The facet joints **52** aid in controlling the motion of the natural spine as is generally understood. These points are referred to in discussing the movement of the vertebra.

FIG. **4** shows a side (lateral) view of two vertebrae, showing typical movements of a cervical vertebra in flexing/extending forwards and backwards. It is observed that the posterior **54** and anterior **58** of the vertebra **50** move differently relative to vertebra **46**. The anterior **58** of vertebra **50** exhibits a greater amount of vertical movement than the posterior **54** of vertebra **50**. It is also observed that the movement of vertebra **50** involves a considerable amount of sliding movement relative to vertebra **46**. The disc **62** between the vertebrae is quite conforming, and changes shape to allow for the movement of the vertebrae, such as for the forward and backward movement of the vertebra **50**. While the present invention discusses the artificial joint in the context of a joint for cervical disc replacement, it will be appreciated that it may be used for replacing other spinal discs as well, typically by modifying the size of the artificial joint and possibly by modification of the shape of the projections and recesses slightly to control the motion and achieve a desired range of motion.

FIG. **5**A shows a top view of vertebra **50**, illustrating the horizontal movement of various points of the vertebra during lateral bending. The posterior **54** of the vertebra **50** remains in substantially the same location during lateral bending. The anterior **58** and center **66** of the vertebra **50** pivot relative to the posterior **54** of the vertebra, moving in arcuate movements as indicated by arrows **70** and **74**. The left side **78** and right side **82** of the vertebra **50** also move in arcuate movements as though pivoting around the posterior **54** of the vertebra, indicated by arrows **86** and **90**.

FIG. **5**B shows a front view of the vertebra **50**, illustrating the vertical movement of various points of the vertebra during lateral bending. Vertebra **46** and disc **62** are also shown so as to illustrate the movement of vertebra **50** relative to vertebra **46**. In lateral bending, the anterior **58** of vertebra **50** moves horizontally relative to vertebra **46**, as indicated by arrow **94**. Left side **78** and right side **82** of vertebra **50** move vertically as well as horizontally, as indicated by arrows **98** and **102**.

As illustrated by FIGS. **5**A and **5**B, lateral bending of the vertebra **50** is a complex movement. The vertebra **50** both slides and twists sideways. The vertebra **50** slides across the disc **62**, pivoting around a posterior point **54** of the vertebra **50**. As the left side **78** or right side **82** of the vertebra **50** move sideways, they move vertically, twisting the vertebra **50** relative to vertebra **46**. As mentioned above, lateral bending typically involves coordinated movements of multiple spinal joints to achieve the desired movement. FIGS. **5**A and **5**B describe a desired movement of a single spine joint in order to accommodate the natural lateral bending of the spine.

FIG. **6**A shows a top view of the vertebra **50** illustrating the horizontal movement of various points of the vertebra during rotation of the vertebra **50**. The vertebra **50** rotates about a point **66** slightly behind the center of the vertebra. As such, the anterior point **58**, posterior point **54**, and lateral points **78**, **82** move according to arrows **56**, **60**, **80**, **84** as shown. FIG. **6**B shows a front view of the vertebra **50** as well as vertebra **46** and disc **62**, illustrating the horizontal movements of the vertebra **50** during rotation thereof. The vertebra **50** undergoes some vertical lifting as wells as tilting towards the side of rotation (i.e. tilting to the left side during a left rotation) as is indicated by arrows **96**, **100**, **104**.

Prior art artificial discs, such as that shown in FIG. **1**, involve a ball and socket type configuration, or a hemispherical disc between two sockets, etc. It is appreciated that the prior art artificial vertebra of FIG. **1** does not move in a similar fashion as the natural vertebra as discussed in FIGS. **3**-**6**. FIG. **7**A shows the movement of the prior art artificial disc which is typical to both flexion/extension and lateral bending. The posterior **106** and anterior **110** of the upper vertebral surface **10** move according to the arrows **114**, **118**. It is appreciated that this movement is quite different than the flexing/extending movement and lateral bending movement of the natural spine as shown in FIG. **4**. The lateral bending movement of the artificial disc is similar to the flexing movement, whereas the natural spine bends laterally with a combination of rotation and flexing movement. The compressive forces present in the body (such as the weight of the body and the tension of the muscles and tendons, etc.) tend to return a natural vertebra to a neutral flexing position, where compressive forces applied to the prior art artificial disc tend to move the prior art disc to an extreme flexing or bending position, away from the neutral position.

FIG. **7**B shows a top view of the prior art artificial disc of FIG. **1** illustrating the rotational movement of the resulting joint. The upper vertebral surface **10** pivots about the center **122** as shown by arrows **126**. The ball and socket type artificial disc pivots about the center of the disc and pivots without any vertical movement of the disc. As shown in FIGS. **5** and **6**, a natural vertebra pivots about a point more towards the rear of the disc in combination with some lifting and tilting, which the prior art artificial discs do not adequately replicate. The compressive forces present in the body (such as gravity and muscle tension, etc.) bias the natural vertebra into a neutral pivotal position, while the prior art artificial vertebra is not biased into a neutral position.

It is thus better appreciated how the prior art artificial disc results in joints which lack inherent stability (can not center themselves or are not biased to a neutral position by the natural compressive forces acting on the spine) and which fail to recreate the movement of the natural spine. Both of these factors result in unnatural movement and place additional stress on the muscles, connective tissues, and supporting joints which operate the particular spinal joint. Thus, the prior art artificial disc can contribute to further failure of the spine.

Turning now to FIG. **8**, a disassembled perspective view of an artificial joint **130** according to the present invention is shown. The joint **130** includes an upper portion **134** having a plurality of projections **138***a*, **138***b*, **138***c* (generally **138**) and a lower portion **142** having a plurality of recesses **146***a*, **146***b*, **146***c* (generally **146**). The projections **138** are received in the recesses **146** when the artificial joint is assembled to replace a disc in the spine. The recesses **146** define the surface which the projections **138** contact and define the possible ranges of movement of the projections, and thus the movement of the upper surface **134** relative to the lower surface **142**. The interaction between the surface of the projections and the surface of the recesses provides controlled movement of the artificial joint **130** which more closely resembles the movement of the natural spine.

In showing the present invention in the following figures and in discussing the present invention, the recesses and projections are often denoted by a bounded area. It is appreciated from the following discussion and figures that the projections and recesses are often smoothly contoured and transition gradually from the surrounding material. Thus, there may not be a sharply defined edge to the projection or recess. The defined boundaries of the recess, for example, may represent the area in which the projection is intended to move, or the area which contacts the projection during expected use of the artificial joint. In some configurations of the artificial joint, the projection or recess may have a more sharply defined edge, such as when a retaining wall is used to provide a positive limit to the range of motion of the artificial joint. In other configurations, the recess may be unbounded or have no distinct edge, and may have another structure such as a pin to limit the movement of the upper surface relative to the lower surface. Thus, it is understood that the term recess is used broadly to define the general area or portion which receives a projection, and is not intended to limit the structure to a structure having opposing sidewalls or an elongate nature.

The following figures and description will better describe the profiles of the projections **138** and recesses **146** and the resulting range and types of movement allowed by the artificial disc **130**. It will be appreciated by the figures and discussion that the recesses **146** need not necessarily have steeply sloped vertical edges to as to absolutely contain the projection **138**, but may present a gradual transition from the adjacent surface of the lower surface **142**. The term recess is used to describe the surfaces which are contacted by the projections **138** and across which the projections slide to allow for movement of the artificial disc **130**.

The upper surface **132** of the upper portion **134** and the lower surface **144** (not visible) of the lower portion **142** are configured for attachment to bone to thereby form an artificial joint. Thus, the attachment surfaces **132**, **144** may have spikes, porous structure, chemicals to induce bonding to the bone, etc. as is known in the prior art. These surfaces are not detailed in every drawing, but are understood to be part of all of the artificial joints disclosed herein as may be necessary. Additionally, the base of the upper portion **134** and/or lower portion **142** may be tapered in thickness such that the resulting artificial disc **130** is wedge shaped and not flat. A wedge shaped artificial disc is useful in addressing lordosis, kyphosis, scoliosis, or other conditions present in a patient's spine. The use of artificial joint elements having a tapered thickness so as to produce a wedge shaped artificial disc is understood to be part of all of the artificial joints disclosed herein. It will be appreciated that such attachment structures or tapering thicknesses may not be necessary in all situations, or may often be of a different size or configuration, especially in situations such as where the artificial joint is sized for a nuclear replacement.

FIG. **9** shows a partially cut-away top view of the joint **130**, illustrating one possible configuration of the projections **138** and recesses **146**. The lower portion **142** and recesses **146**, as well as a cross-sectional view of the projections **138** are visible. The remainder of the upper portion **134** is omitted for clarity. (While discussed in this application as the projections extending downwardly from the upper portion into the recesses in the lower portion, it will be appreciated that the configuration can be reversed so that the projections extend upwardly from the lower portion into receptacles in the upper portion while maintaining the stability discussed herein).

FIG. **9**, and many of the following figures are taken along line **9**-**9** of FIG. **8**, and are used to indicate the shapes and orientation of the projections and recesses and configuration of the artificial joint.

The projections **138** are formed as hemispherical projections on the upper portion **134**, and are illustrated with cross-hatching to distinguish from the recesses **146**. The recesses **146** are formed in the lower portion **142**. The recesses may be formed as hemispherical recesses, or may be formed as oval, kidney, or egg shaped recesses. For example, the anterior recess **146***a* may be formed as an oval recess having a long axis extending sideways. The lateral recesses **146***b*, **146***c* may be formed as oval recesses having a long axis extending somewhat parallel to the adjacent edge of the lower layer **142**. Regardless of the shape, it is preferred that the recesses be larger from side to side than adjacent portions of the associated projection so that the projection is provided some degree of translational movement prior to engaging the sidewalls (which are generally sloped rather than vertical) of the recesses.

As is more specifically illustrated in subsequent figures, the receptacles are typically contoured to control the movement of the resulting artificial joint. Typically, the bottom portion of the receptacles **146** is relatively flat to allow some translational movement, and the inward sides of the receptacles are increasingly sloped to cause a lifting of the upper portion **134** as a particular side thereof slides towards the center of the lower portion **142**. The outer portions of the receptacles **146** may simply continue in the direction of the lower portion of the receptacles, or may contain a retaining wall or steeply sloped surface which limits the motion of the artificial joint **130**. It is not intended that the projections **138** will climb such a sloped outer portion of the receptacles **146** so as to lift the side of the upper portion **134** which is moving away from the center of the lower portion **142** as such is typically contrary to the motion of the natural spine.

Additionally, the recesses **146** may be oriented at various angles to aid in controlling the movement of the joint. The anterior recess **146***a* may be oriented so as to be directed somewhat forwards rather than completely vertically. The lateral recesses **146***b*, **146***c*, may be oriented somewhat backwards and out the lateral sides.

FIG. **10** shows a side view of the lower portion **142** of FIG. **9**. It can be more clearly seen how the anterior recess **146***a* is oriented in a forwards direction rather than completely vertically, and how the lateral recesses **146***b* (not shown), **146***c* are oriented such that they are tilted outwardly and backwards from a completely vertical orientation. The orientation of the recesses **146** aids in controlling the movement of the projections and upper portion; thus controlling the movement of the artificial disc **130**. The movement of the artificial disc **130** will be discussed in greater detail in the following figures and description.

FIG. **11** shows another partially cut-away top view of the artificial disc **130**, illustrating an alternate configuration of the projections **138** and recesses **146**. The projections **138** are formed so as to have sides which are generally aligned in a radial alignment with a posterior point **150**, as indicated by the dashed reference lines extending from the posterior point **150**. Similarly, the contours of the receptacles **146** generally follow those radial lines. Such a radial alignment encourages the disc to rotate about the posterior point **150**, imitating the movement of the natural spine as discussed above.

As the disc rotates, the anterior projection **138***a* moves laterally as is illustrated by arrow **148**, and the lateral projections **138***b*, **138***c* move as illustrated by arrows **152** and **156**. As the upper portion **134** rotates to the right, left lateral projection **138***c* is raised vertically (out of the page) as it engages the sidewall of the recess, thereby imitating the tilting of the natural spine during rotation. When the upper surface **134** is rotated to the left relative to the lower surface **142** the right lateral projection **138***b* is raised in a similar manner. These movements are also shown in FIGS. **13-15**.

FIG. **12** shows another partially cut-away view of the artificial disc **130**, illustrating an alternate configuration of the projections **138** and recesses **146**. The lateral projections **138***b*, **138***c*, and lateral recesses **146***b*, **146***c* have been formed such that they are slightly curved. The curve encourages the upper portion **134** to rotate around point **154** relative to the lower portion **142**. The curved surfaces of the lateral projections **138***b*, **138***c*, and lateral recesses **146***b*, **146***c* aid in constraining the rotational movement of the disc **130** to a predetermined motion.

Point **154** is somewhat forward of the posterior portion (indicated at point **158**) of the disc **130**, but behind the center **162** of the disc. As the upper portion **134** of the disc **130** is rotated, the anterior projection **138***a* moves according to arrow **166**, and the lateral projections move according to arrows **170** and **174**. The shape of the recess **146***c* cause the left lateral projection **138***c* to be raised vertically when the upper portion **134** is pivoted to the right, and the shape of the recess **146***b* causes the right lateral projection **138***b* to rise when the upper portion is pivoted to the left—thus imitating the tilting of the natural spine when rotating.

FIG. **13**A shows a cross-sectional view of the artificial discs **130** of FIGS. **8** through **12** along line **13-13** (as indicated in FIG. **12**). The cross section shows both the upper portion **134** and lower portion **142** of the artificial disc **130** as included in FIG. **8**, but the section line is shown in FIG. **12** for clarity in indicating the section shown. It can be observed how the projections **138***b* and **138***c* have rounded lower surfaces to allow for smooth sliding movement (rotation and translation) across the surfaces of the recesses **146***b*, **146***c*. The recesses **146***b*, **146***c* are also smoothly formed, providing for smooth and continuous movement across a desired range of movement. In a resting position the bottom of the projections **138***b*, **138***c* rest on the generally flat bottoms of the recesses **146***b*, **146***c*. Thus, the joint is highly stable, as it requires no additional work for the joint to be held in a resting state. The compressive forces exerted on the joint, such as that of the weight of the body and the tension of surrounding tissues, will tend to bias the joint into such a resting state. The joint's resting state is energetically stable (an energetic minimum) and corresponds to the neutral position of the natural spine.

When the upper portion **134** is slid to the right relative to the lower portion **142** (as occurs in the natural spine), the left projection **138***c* is raised as it travels upwardly along the surface of recess **146***c*. The right projection **138***b* moves generally horizontally across the generally flat bottom of recess **146***b*, resulting in a tilting of the upper portion **134** to match that of the natural spine, and resulting in a net expansion of the artificial disc. Left movement of the upper surface **134** causes the right projection **138***b* to be raised vertically along the sidewall of the recess **146***b*, while the left projection **138***c* slides generally horizontally, tilting the upper portion **134** to the left and resulting in a net expansion of the artificial disc. By matching the travel and curvature of the projections **138** with the sidewalls of the recesses **146**, the upper surface **134** can be made to closely resemble the travel which occurs in the natural spine. It is thus appreciated that the compressive forces placed on the spine such as the weight of the body above the artificial joint and the tension in the tissues surrounding the natural spine will urge the artificial joint back into the neutral position, as these forces act to compress the artificial joint. The artificial joint **130** is thus naturally stable as these compressive forces tend to return the upper portion **134** to its original neutral position. Thus, additional fatigue is not placed on the muscles and connective tissue, increasing joint stability.

FIG. **13**B shows the artificial joint of FIG. **13**A with the upper portion displaced slightly to the right. It can be seen how the projection **138***c* is raised as it moves to the right and how the upper portion **134** is tilted to the right. It can be seen how the average distance between the upper portion **134** and lower portion **138** is increased, resulting in a net expansion of the artificial joint. Thus, compressive forces acting on the joint **130** counteract the expansion of the joint and return it to a neutral position.

The expansion of the artificial joint caused by movement thereof may be described in different ways. The volume occupied by the joint, including the volume of the upper portion **134**, lower portion **138**, and the space directly therebetween, increases in response to displacement of the joint from a neutral position. Alternatively, the mean distance between the upper portion **134** and the lower portion **142** increases when the joint is displaced from a neutral position. While various different terms may be used to describe the expansion of the joint **130**, the design of the artificial spinal disc of the present invention is such that, for the intended range of motion of the resulting artificial joint, the artificial joint is expanded as a result of the displacement of the joint from a neutral position and therefore compressive forces placed on the artificial joint will bias the joint back into a neutral position. This produces a joint which is inherently stable as the forces normally placed on the joint while in use tend to restore the joint to a neutral position. For the most preferred embodiments of the artificial joint, the joint experiences a net expansion for all types of desired movement, resulting in a joint where all types of movement are counteracted by compression of the joint, and thus a joint where the compression naturally placed on the spine biases the joint into a neutral position in reaction to all types of movement from neutral.

FIG. **13**C shows an artificial joint similar to that of FIGS. **13**A and **13**B, but where the projections **138** (lateral projections **138***b*, **138***c* shown) are formed on the lower portion **142** and the recesses **146** (lateral recesses **146***b*, **146***c* shown) are formed on the upper portion **134**. It is seen that the direction of slope of the recesses **146** is reversed to achieve the same direction of tilt during movement of the artificial joint **130**. That is that where FIG. **13**A shows recesses where the sections adjacent the outer edges of the lower portion are generally horizontal and the sections adjacent the interior of the lower portion are sloped, FIG. **13**C shows recesses **146** where the sections adjacent the outer edges of the upper portion **134** are sloped and the sections adjacent the interior of the upper portion are generally horizontal. The arrangement shown in FIG. **13**C ensures that the upper portion **134** is tilted forwards when extending forwards, etc. to match the natural movement of the spine as has been discussed.

It is thus appreciated that the artificial joints of the present invention may not always have projections **138** on the upper portion **134** and recesses **146** on the lower portion **142**, but may contain projections on the lower portion and recesses on the upper portion, or a combination of both projections and recesses on the upper portion and on the upper portion. Generally, when it is desirable to have a projection **138** on the lower portion **142** of the joint and a recess **146** on the upper portion **134** of the joint, the relative orientation of the recess is reversed so that sloping portions which were placed on the inside of the recess (nearest the center of the joint) are placed on the outside of the recess and generally planar or less sloped portions which were placed on the outside portion of the recess are placed on the inside portion of the recess. In most cases, however, it is easier to manufacture an artificial joint where the projections are on the top of the joint and the recesses are on the bottom of the joint.

FIGS. **14**A and **14**B show cross-sectional views of the artificial discs **130** of FIGS. **8** through **12** along line **14-14**. The cross section shows both the upper portion **134** and lower

portion **142** of the artificial disc **130** as included in FIGS. **8** through **12**, but the section line is shown in FIG. **12** for clarity in indicating the section shown. It can be seen how the lateral projections **138***b*, **138***c* (right lateral projection **138***b* not shown) move upwardly as the upper portion **134** is moved forwards (towards the anterior of the lower surface **142**). The lateral projection **138***b*, **138***c* slides upwardly and forwards across the surface of the recess **146***b*, **146***c*. Thus, the upper portion **134** is pivoted upwardly at the rear about 5-7 degrees, thereby simulating the movement of the natural spine. The anterior projection **138***a*, not shown, may either slide horizontally, or may even slide downwardly along the slope in the anterior recess **146** to provide the diving motion at the front of the joint similar to a natural spine. Unlike prior art artificial joints, however, the joint is configured to return to its original position once the associated muscles are released, using the compressive forces acting on the joint to slide the projections **138***b* and **138***c* back down the sidewalls of their associated recesses, and to slide or raise the anterior projection **138***a* back to its original position.

FIG. **15** shows a cross-sectional view of the artificial discs **130** of FIGS. **8** through **12** along line **15-15**, with the addition of a motion limiting post or stop which is not shown in the previous figures. The cross section shows both the top and bottom of the artificial disc as included in FIGS. **8** through **12**, but the section line is shown in FIG. **12** for clarity in indicating the section shown. The anterior projection **138***a* and recess **146***a* are visible. As the upper portion **134** moves backwards (towards the posterior of the lower surface) the anterior projection **138***a* is raised vertically as it slides up the inclined surface of the recess **146***a*. In order to limit the movement of the upper portion **134** relative to the lower portion **142**, one of the upper portion and lower portion may have a post **178** formed thereon (not shown in previous figures) and the other portion may have a corresponding hole **182** or receptacle to receive the post **178**. Various different methods and structures may be used to affirmatively limit the motion of the artificial joint.

The limiting of the movement of the post **178** to space defined by the hole **182** constrains the movement of the upper surface **134** relative to the lower surface **142**, and thus constrains the range of motion provided by the artificial disc **130**. This may be important in preventing the artificial disc **130** from being dislocated (the upper surface **134** moving too far across or off of the lower surface **142**) as may occur in an accident or other forceful impact.

The movement of the cervical vertebrae is relatively small. For example, in flexing/extending forwards and backwards, a vertebra may tilt forwards by about 10 degrees and backwards by about 5 degrees. The same movement may typically involve the vertebra sliding about 1 or 2 millimeters relative to the vertebra below. In rotating, the vertebra may pivot by about 4 degrees and slide about 0.5 or 1 millimeter relative to the vertebra below. Thus, the hole **182** may be about 4 millimeters larger than the diameter than the post **178**.

FIGS. **13-15** illustrate how the recesses **146** are shaped to both direct the movement of the projections **138** into predetermined directions and to selectively raise one or more of the projections as the upper portion **134** is moved. The projections are directed into movements which imitate the motion of the natural spine. As the artificial disc **130** is flexed forwards, the upper portion **134** slides forwards and is also tilted forwards as the lateral projections **138***b*, **138***c* are raised vertically by recesses **146***b*, **146***c*.

As the artificial disc rotates, the projections **138** and recesses **146** also aid in imitating the movement of the natural spine. For example, when the upper portion **134** is rotated to the right, the anterior projection **138***a* will slide to the right, the left lateral projection **138***c* will slide to the left and somewhat forwards, and will be raised vertically, and the right projection **138***b* will slide to the left and slightly backwards. By controlling the shape of the projections **138** and the shape and curvature of the bottom and sidewalls of the recesses **146**, the three dimensional movements of the upper portion **134** and the lower portion **142** can be carefully controlled. Thus, an artificial joint can be created which much more closely simulates the movements of the natural spine than the artificial joint of FIG. **1**.

FIG. **16** shows a detailed view of a projection **138** and recess **146** of the artificial disc **130**. Only one projection **138** and recess **146** are shown for clarity, but the principles discussed apply to each of the projection **138**/recess **146** combinations. The recesses **146** may be formed with a generally flat and horizontal lower section **186**, a curving transitional section **190**, and a more steeply inclined section **194**. The projection **138** is formed with a rounded end **198** which may slide smoothly across the recess **146** including transitioning smoothly across the various sections of the recess. It will be appreciated that different shapes of projections and recesses, such as curving sections **190** which curve more rapidly or slowly to increase the rate of rise of the upper portion **134** relative to the translational movement thereof, may be used to alter the characteristic motion of the artificial joint.

The projection **138** may be located in a resting position in the transitional section **190** of the recess, such that the projection **138** will slide in a generally horizontal direction when sliding away from the inclined portion **194** (to the left in FIG. **16**), and such that the projection will immediately begin to move upwards as well as horizontally as the projection slides towards the inclined portion of the recess **146** (to the right in FIG. **16**). Such a configuration of the projections **138** and recesses **146** may be used to create an artificial disc which is self centering and energetically stable.

The projections **138** and recesses **146** may be oriented such that the projections slide generally horizontally when sliding generally away from the center of the lower portion **142**, and such that the projections slide both horizontally and upwardly when sliding generally towards the center of the lower layer **142**. Thus, when the artificial disc is moved forwards, as would occur in a forwards flexion of the spine, the anterior projection **138***a* slides generally forwards and the lateral projections slide both forwards and upwards across the transitional portion **190** and inclined portion **194** of the lateral recesses **138***b*, **138***c*. Thus, the posterior portion of the upper layer **134** of the artificial disc **130** is raised upwardly, causing a rising of the body weight and tissue supported above the artificial disc **134**. The raising of the upper portion **134** and the weight supported thereon is against the force of gravity and against the tension of the muscles and tissues supporting the spine. Thus, the compressive forces of the body weight placed on the joint and the tension in the supporting tissue will cause the joint to return to a neutral position, lowering the elevated lateral projections **138***b*, **138***c* and lowering the upper portion **134** and supported weight. A similar mode of operation is achieved in rotational movement of the artificial disc **130**.

While discussed relative to forward flexion, it will be appreciated that each recess **146** may be provided with sloped sidewalls about the entire circumference, thereby selectively controlling the lifting of an associated projection **138** in response to any direction of horizontal movement. By matching the curvature of the projections **138** and the curvature of the recesses **146**, substantial control of the three dimension movement of the upper portion **134** is provided.

The artificial disc **130** is thus advantageous over the prior art, as the disc results in a joint which is energetically stable or self centering and which is biased back into a neutral position, where prior art artificial discs result in joints which are gravitationally unstable and biased further from a neutral position once moved from neutral. Additionally, the artificial joints **130** results in a motion which closely approximates the natural motion of the spine. Matching more closely the natural motion of the spine reduces the adverse impact on the tissue surrounding the artificial joint when in use and promotes the long term success of the artificial joint.

FIG. **17** illustrates an alternate configuration of a projection **138** and recess **146** of the artificial disc **130** to limit the range of motion of the resulting joint. The projection **138** has been formed with a rounded end **202** which more steeply curves away from the contact point with the recess **146**. The recess **146** has been formed with an inner retaining wall **206** and an outer retaining wall **210**. The projection **138** will contact one of the retaining walls after moving to an extreme position within the recess **146**. Any or all of the recesses may be thus formed with retaining walls to limit the movement of the upper surface **134** relative to the lower surface **142**. Thus, the space between the retaining walls **206**, **210** and the projections **138** when the projection is in a resting position will determine range of motion of the upper surface **134**, and of the joint resulting from the artificial disc **130**.

The retaining walls **206**, **210** may extend completely around the recess **146** and connect each other, or may be formed as separate structures. It will be appreciated that inner retaining walls **206** may not be necessary. If each of the recesses **146** is formed with an outer retaining wall **210**, the range of movement of the projections **138** and upper surface **134** will be limited in all directions by the outer retaining walls **210**. Similarly, outer retaining walls may not be necessary if the joint is completely restrained by inner retaining walls.

The inner retaining walls **206** may be used to more precisely control the movement of the projections **138** and upper surface **134** in selected directions. FIG. **18** shows such a use. For example, inner retaining walls **206***b*, **206***c* may be placed on the inside sides of recesses **146***b*, **146***c*. The inner retaining walls **206***b*, **206***c* prevent movement of the lateral projections **138***b*, **138***c* in a purely lateral direction. The inner retaining walls **206***b*, **206***c* are positioned against the lateral projections **138***b*, **138***c* such that, in rotation, the lateral projections **138***b* **138***c* do not translate laterally but rotate about a point of contact between a lateral projection and inner retaining wall.

For example, if the upper portion **134** is rotated to the right, the lateral projections **138***b*, **138***c* can not simply translate to the left or right. The left lateral projection **138***c* may move forwards and to the right and the right lateral projection **138***b* may move backwards somewhat. The anterior projection **138***a* may move to the right and forwards. The left lateral projection **138***c* is raised vertically as it moves, as discussed previously. It is thus seen that the inner retaining walls **206***b*, **206***c* aid in constraining the movement of the artificial disc to imitate the movement of the natural spine. The inner retaining walls cause the center of rotation to be roughly between the retaining walls, closer to the posterior end of the artificial disc, where the center of rotation of the natural spine is located.

In forwards and backwards flexing/extending, the upper portion **134** should move as shown by arrows **214**, **218**, **222**, in a manner similar to the natural spine. In rotation, the upper surface should move as shown by arrows **226**, **230**, **234**, also in a manner similar to that of the natural spine.

It will be appreciated that it may not be possible to perfectly replicate the movement of the natural spine and still achieve an artificial disc **130** which is sufficiently stable. As such, the resulting design may be a compromise between matching the natural motion and providing inherent stability and self centering capabilities, for example. An artificial joint may also be a compromise which provides a good match to the natural motion, inherent stability, and which may be manufactured from a desired material without excessive expense or difficulty. The present invention, however, does provide a marked improvement over the inherently unstable artificial discs of the prior art and much more closely replicates the natural movements of the spine.

FIG. **19** shows another partially cut-away view of an artificial disc **130'** of the present invention. The upper surface **134'** (FIG. **20**) includes an anterior projection **138*d*** and a posterior projection **138*e***. The lower surface **142** includes an anterior recess **146*d*** and a posterior recess **146*e***. While the two projection/recess design may not provide an artificial joint which is as stable as a three or more projection design, it still provides a marked improvement in stability and movement over a conventional artificial disc. For example, the elongate configuration of the projections **138*d*** and **138*e*** minimizes the effort necessary to center the joint compared to a hemispherical single projection as in the prior art.

FIG. **20** shows a cross sectional view of the artificial disc **130'** of FIG. **19** along line **20-20**. The projections **138** and recesses **146** configured as shown will cause the anterior projection **138*d*** to slide forwards (to the left) and the posterior projection to slide forwards and upwards during a forwards flexing of the artificial disc **130'**, tilting the upper portion **134'** forwards and sliding the upper surface in a manner similar to the natural spine.

Similarly, the posterior projection **138*e*** will slide backwards and the anterior projection **138*d*** will slide backwards and upwards along the recesses **146** during a posterior extending of the artificial disc, tilting the upper portion **134'** backwards and sliding the upper portion similar to the natural spine. The upward movement of the upper portion **134'** during the forwards and backwards flexing/extending of the artificial disc will move the supported body against gravity, and cause gravity to bias the artificial disc back into a neutral position, as discussed above.

In rotation, the upper portion **134'** will rotate roughly around the center of the artificial disc **130'**, and the upper disc will be raised slightly as the edges of the projections **138** contact the inclined portions of the recesses **146**, causing gravity to bias the artificial disc **130'** into a neutral position. By modifying the configuration of the projections and recesses, the upper portion **134'** can be made to rotate about an axis other than at the center of the upper portion. Thus, an artificial joint may be provided which more accurately resembles the movement of the natural spine.

It will be appreciated that the two projection artificial disc **130'** of FIGS. **19** and **20** may not approximate the movement of the natural spine quite as closely as the three projection artificial disc **130** of FIGS. **8** through **18**, but it may be easier to manufacture. Furthermore, it remains more stable than the artificial joints of the prior art.

FIG. **21** shows a perspective view of another artificial disc which is similar to that of FIGS. **8-18** and functions in a similar manner. The disc is different in that the anterior projection **234**, as formed on the top **238** of the joint, has a more abruptly terminated anterior side. The bottom **242** is formed with a recess **246** which has a corresponding shape. The lateral projections **250**, (**254** not shown) and lateral recesses **258**, **262** may be formed with similar shapes as that of projection **234** and recess **246**, or may be more smoothly shaped as shown previously.

FIG. **22** shows a cross-sectional view of the joint of FIG. **21** taken along line **22-22**. It can be seen how the nearly vertical anterior side of projection **234** and the nearly vertical anterior side of the recess **246** will prevent the upper portion **238** from moving more than a short distance to the right relative to the lower portion **242**, providing a motion limit. Providing such a motion limit helps ensure that the artificial joint is not hyperextended once installed into a patient. As has been discussed previously, the recess **246** may be shaped such that the projection **234** will move relatively horizontally when moving to the right from the neutral position shown, and such that the projection moves vertically as well as to the left when moving to the left relative to the base and from the neutral position shown. As has been discussed, this creates a stable joint wherein compressive forces on the joint bias the joint into a neutral position. It will be appreciated that one or more of the projections and recesses may be formed in such a manner to thereby limit the motion of the joint. One or more of the different methods of limiting the motion of the artificial joint discussed herein may be used with any of the different joint configurations shown herein.

FIG. **23** shows another artificial disc **264** which uses a single projection and a single recess to achieve the stability and motion control discussed herein. The top **266** includes a single recess **270**, and the bottom **274** includes a single projection **278**. The recess **270** and projection **278** are formed with rounded and/or angled engaging surfaces so as to provide for smooth motion therebetween. The projection **278** and recess **270** may be formed as polygonal shapes or other shapes to limit the rotation of the artificial joint and provide more natural motion of the joint. It will be appreciated that a circular lobe **278** and recess **270** will not limit the rotation of the top **266** relative to the bottom **274** of the joint. The projection **278** and recess **270** may be formed as ovals, squares, triangles, or other shapes.

FIG. **24** shows a cross sectional view of the artificial disc **264**. It can be seen how the recess **270** includes sloping outer wall **282** which transition from the center of the recess and rounded shoulders **286**, and how the projection **278** also has a sloping transitional region **290** and rounded shoulders **294**. The shoulder **294** of the projection contacts and slides across the sloping outer wall **282**, and the shoulder **286** of the recess **270** contacts and slides across the sloping transition region **290** of the projection.

In viewing the artificial joint **264**, it can be appreciated that if the top **266** is moved to the right relative to the bottom **272**, the right side of the top will move generally horizontally across the generally horizontal surfaces, and the left side of the top will be raised as the shoulders **286**, **294** engage and move across the sloping transition regions **282**, **290**. This will be the case for lateral bending or flexion/extension of the artificial joint **264**. Thus, the artificial joint **264**, while not perfectly approximating the natural motion of the spine, will create a similar motion and will create a joint which is biased into the neutral position shown by compressive forces applied to the joint (as is the case when a joint is installed in a human spine). In order to better control the motion of the artificial joint **164**, the upper portion **266** may be curved away from the contact points on the shoulders **286** as indicated at **292**. Additionally, the lower portion **274** may slope downwardly in the posterior portion as indicated at **296** so as to more closely approximate the natural motion of the spine.

FIG. **25** shows a bottom view of a top portion **298** of an artificial joint similar to that shown in FIGS. **23** and **24**. It can be seen how the recess **302** (and the corresponding projection formed on the bottom of the joint) may be formed in shapes other than a square or rectangular shape as shown previously. Different shapes of projections and recesses will alter the characteristic motion of the resulting joint. For example, a projection/recess shaped as shown may tend to lift more when moving in one direction than in the opposite direction or provide different rotational characteristics during rotation or lateral bending of the joint. Thus, a shape may be selected which reasonably approximates the motion of the natural spine and creates a joint which is biased into a neutral position by compressive forces, but which is also a relatively simple shape to manufacture.

FIG. **26** illustrates the use of an artificial joint **306** of the present invention used to replace the nucleus of a damaged spinal disc, while leaving the annulus **310** (annulus fibrosis) of the natural disc in place. Leaving the annulus **310** as intact as is possible may be advantageous in some cases as it provides support to the artificial joint **306**, helping to keep the joint **306** centered over the vertebra **314** or helping to keep the top of the joint centered over the bottom of the joint. An artificial joint which is used for a nuclear replacement will typically be smaller than a joint used for a total disc replacement. Any of the joint designs shown above may be used as either a total disc replacement or a nuclear replacement if manufactured in the appropriate size and configuration and made of an appropriate material.

FIG. **27** illustrates an artificial disc **318** with an elastomeric band **322** surrounding the joint **318**. The band **322** may aid in loosely constraining the motion of the joint and in keeping the top of the joint centered above the bottom of the joint. Any of the above joint designs may incorporate such a band **322** if desired.

FIG. **28** illustrates an alternate artificial disc according to the present invention. The artificial joint **326** includes a base portion **330** having a circular recess **332** formed therein, a toroid **334**, and a top **338** which includes a conical or frustoconical portion that nests in the toroid **334**. The toroid **334** can translate across the base **330** but is biased into the center of the base by compressive forces. The top **338** may pivot inside of the toroid **334** and is elevated as it pivots because of the interaction between the conical portion and the toroid.

FIG. **29** illustrates the joint of FIG. **28** in a position corresponding to a flexion/extension or lateral bending motion. It can be seen how the toroid **334** is elevated as it slides across the recess **332** in the base **330**, and how the top **338** is elevated as it pivots. The joint **326** utilizes symmetrical shapes which may be relatively easy to manufacture and roughly approximates the natural spinal motion. The flexion/extension and lateral bending of the joint closely approximate the natural spine, and are also biased into a neutral position. While the rotation is unconstrained, this motion may be the easiest for the muscles and surrounding tissue to control and is the least affected by the compressive forces placed on the natural spine.

Turning now to FIG. **30**, an exploded perspective view of another artificial joint is shown. The joint, indicated generally at **350**, is similar to the artificial joints shown in FIGS. **8-22**. The joint **350** includes an upper portion **354** having an anterior projection **358** and two lateral projections **362**. The joint **350** also includes a lower portion **366** which includes an anterior recess **370** and two lateral recesses **374**, which may be connected together into a single recess as is shown. It will be appreciated, however, that the narrow connecting portion as shown does not contribute to the motion of the artificial disc and is a manufacturing convenience. The joint functions as has been discussed previously with respect to FIGS. **8** through **18**. That is to say that the upper portion **354** slides across the lower portion **366** allowing anterior-posterior, lateral, and rotating translational movements. As the upper portion **354** slides across the lower portion **366**, the projections **358**, **362** are also typically moved vertically relative to the lower portion **366** due to the curved surfaces of the recesses **370**, **374**. As will be shown in the following figures, the projections **358**, **362** are generally spherical and the recesses **370**, **374** have circular vertical cross sections. This results in an artificial joint **350** which closely matches the natural motion of the spine and provides inherent stability as discussed above but which is easier to manufacture.

Similar to the artificial joints of FIGS. **8-22**, the projections **358**, **362** are moved upwardly relative to the lower portion **366** as they move towards the center of the lower portion. This vertical movement results in a net expansion of the artificial joint, and thus results in a joint where compressive forces applied to the joint bias the joint back towards a neutral position. This vertical motion also results in a joint which provides motion that more closely matches the natural kinematic motion of the human spine. It will be appreciated that the slopes and changes of curvature in the recesses **370**, **374** may be adjusted to control the amount of vertical movement generated by a particular horizontal movement.

FIGS. **31** through **34** show additional details of the upper portion **354** of the joint **350** of FIG. **30**. FIG. **31** is a bottom view of the upper portion **354**. FIGS. **32** and **33** are cross sectional views taken along section lines **32** and **33** of FIG. **31**. FIG. **34** is a perspective view of the upper portion **354**. One advantage of the joint **350** is that it uses a somewhat simpler and more uniform surface shape and geometry than the joints of FIG. **11** while achieving a motion which closely replicates the motion of the natural spine. The upper portion may be formed as a substantially flat disc with semi-spherical projections **358**, **362**. The semi-spherical projections **358**, **362** are more easily shaped and polished that the more complex projections such as are shown in FIG. **11**, for example.

FIGS. **35** through **40** show additional details of the lower portion **366** of the joint **350** of FIG. **30**. FIG. **35** shows a top view of the lower portion **366** and FIGS. **36** through **39** are cross sectional views of FIG. **35** taken along section lines **36-39**, respectively. FIG. **40** is a perspective view of the lower portion **366**. As can be seen in FIGS. **30** and **35** through **40**, the two lateral recesses **374** may be connected together across the back lower portion **366** of the artificial joint. While the lateral projections **362** may never move fully to the back of the lower portion **366** directly between the lateral recesses **374**, it may be easier to form and polish the joint with such a configuration.

It can be observed from FIGS. **36** through **39** that the contact surface **378** of the anterior recess **370** (across which anterior projection **358** slides during articulation of the joint) is gently curved and sloped. The contact surface **378** of recess **370** allows the projection **358** to move downwardly as is slides away from the center of the lower portion **366** and upwardly as it slides towards the center of the lower portion, such as during flexion and extension of the joint, as well as upwardly as it moves laterally across the lower portion, such as during rotation of the joint. The curvature of the contact surface **370** results in greater vertical movement per unit of horizontal movement when the projection **358** is closer to the center of the lower portion **366** as compared to when the projection **358** is closer to the outer edge of the lower portion.

In order to facilitate easier manufacture of the lower portion **366**, the recesses **370**, **374** may each have a circular vertical cross section as is visible in FIGS. **37** through **39**. This allows a circular grinding or polishing tool to be swept across the lower portion during manufacture in order to form the recesses.

It can be observed from FIGS. **36-39** that the contact surfaces **382** of the lateral recesses **374** have smaller radii of curvature than that of contact surface **378** of anterior recess **370**. As such, the contact surfaces **382** of the lateral recesses **374** are horizontal or nearly horizontal near the outer edges of the lower portion **366** and more steeply sloped near the center of the lower portion. As a result, the lateral projections **362** experience little or no vertical movement as they move across the surface **382** away from the center of the lower portion **366** and move upwardly away from the lower portion **366** of the joint as they move towards the center of the lower portion. The curvature of the contact surfaces **382** is such that the vertical movement of the lateral projections **362** is greater per unit of horizontal movement when the lateral projections are closer to the center of the lower portion **366**.

The steeper slope of the more central portions of contact surfaces **382** as compared to contact surface **378** provides a net restoring force which biases the artificial joint **350** to a neutral position (i.e. an un-displaced position). Thus, the slope of contact surface **378** will tend to bias the anterior projection **358** away from the center of the lower portion even in a neutral position, but the greater slopes of the lateral contact surfaces **382** will provide a greater bias against further anterior displacement to the lateral projections **362** and maintain the joint in a neutral position while compression is applied to the artificial joint **350**.

The shapes and curvatures of the contact surfaces **378**, **382** of the recesses **370**, **374** results in a kinematic movement of the artificial joint **350** which approximates that of the natural spine and which also tends to return the artificial joint **350** to a neutral position when the joint **350** is placed under compression. A neutral position is where the upper portion is aligned over the lower portion and not displaced from the center thereof. (It will be appreciated that upper or lower portions may have a base which is shifted somewhat from the projections so that the upper and lower base portions are somewhat misaligned even though the projections and recesses are in a neutral orientation. Such is within the scope of the invention.) In use, the artificial joint **350** will be biased towards an un-displaced, neutral position by the compressive forces placed upon the joint by the body and will therefore stabilize the joint. The artificial joint **350** presents a good approximation of the natural movement of the spine, i.e. the rotation and translation which occurs with lateral bending or rotation of the spine and the translation which occurs with flexion and extension of the spine.

Turning now to FIGS. **41** through **53**, another artificial spinal joint **386** of the present invention is shown. The artificial joint **386** operates according to the principles discussed above in that the artificial joint provides a motion that closely matches the natural motion of the spine and which is inherently stable. The joint **386** is stable in that the joint experiences a net expansion as a result of the intended ranges of motion and thus the compressive forces placed on the joint while in a spine will tend to restore the joint to a neutral, unbiased position.

FIGS. **42** through **46** show the upper portion **390** of the joint **386** of FIG. **41** while FIGS. **48** through **53** shows the lower portion **394** of the joint. FIG. **42** shows a perspective view of the upper portion **390**. FIG. **43** shows a bottom view of the upper portion **390** and FIGS. **44** through **47** show cross sectional views of the upper portion taken along section lines **44** through **47** of FIG. **43**. Similarly, FIG. **48** shows a perspective view of the lower portion **394** while FIG. **49** shows a top view of the lower portion **394** and FIGS. **50** through **53** shows cross sectional views of the lower portion taken along section lines **50** through **53** of FIG. **49**.

The joint **386** differs from the joints discussed above in FIGS. **8** through **18** and **30** through **40** in that it contains a single posterior projection **398** and posterior recess **406** and two anterior lateral projections **402** and two anterior lateral recesses **410**. Otherwise, the upper portion **390** and lower portion **394** mate together in a similar manner and function in a similar manner to that discussed above.

The joint **386** includes two anterior projections **402** and a single posterior projection **398** and corresponding recesses so as to better utilize the stabilizing effects of the facet joints (**52** of FIG. **3**). During forward flexion of the joint **386**, more pressure is placed on the two anterior projections **402** and anterior recesses **410**, providing greater lateral stability. During backwards extension of the joint **386**, more pressure is placed on the single posterior projection **398** and posterior recess **406** which results is somewhat less lateral stability than is provided in forward flexion of the joint. However, the facet joints **52**, which are found on the posterior of the spine, provide additional lateral stability during extension of the joint **386**. Thus, the two lateral projections **402** and recesses **410** are better utilized on the anterior of the joint **386**.

Otherwise, the joint **386** of FIGS. **41** through **53** is similar to the joint **350** of FIGS. **30** through **40**. As illustrated in FIGS. **44** through **47**, the projections **398**, **402** have spherical shapes to allow for easier grinding and polishing of the upper portion **390** when a material such as polycrystalline diamond (PDC) is used. The recesses have circular vertical cross sections as illustrated in FIGS. **50** through **53** so as to allow for easier grinding and polishing with a circular rotary tool when using PDC or a similar material. The rotary tool may be swept through a relatively simple horizontal motion to grind the recess shapes shown. The joint **386** has been cut to a trapezoidal shape as such a shape closely matches the available space in the spine for total disc replacement. It will be appreciated that all of the preceding inventive artificial joints, while shown round for ease in drawing and discussing the joints, may be formed in a generally trapezoidal or generally rectangular shape as shown so as to most efficiently interface with the vertebral bodies.

Turning now to FIGS. **54** through **66**, another artificial spinal joint of the present invention is shown. FIG. **54** shows a perspective view of the joint **414**. FIGS. **55** through **60** show the upper portion **418** of the joint **414** while FIGS. **61** through **66** show the lower portion **422** of the joint **414**. FIG. **55** shows a perspective view of the upper portion **418**. FIG. **56** shows a bottom view of the upper portion **418** and FIGS. **57** through **60** show cross sectional views of the upper portion taken along section lines **57** through **60** of FIG. **56**. Similarly, FIG. **61** shows a perspective view of the lower portion **422** while FIG. **62** shows a top view of the lower portion **422** and FIGS. **63** through **66** shows cross sectional views of the lower portion taken along section lines **63** through **66** of FIG. **62**.

The joint **414** is similar to the joint **386** discussed above in that it contains a single posterior projection **426** and posterior recess **434** and two anterior lateral projections **430** and two anterior lateral recesses **438**. The joint **414** is different in that the projections **426**, **430** and recesses **434**, **438** are larger that those of the joint **386** so as to further lower the contact pressure of the joint and further reduce the stress placed on the material used to construct the joint.

The projections **426**, **430** are spherical in shape and the recesses **434**, **438** have circular vertical cross sections so as to allow for simplified grinding and polishing as discussed above, and provide the desired motion as described in the present application to closely match the natural motion of the spine. In order to maximize the stability of the joint **414**, the projections **426**, **430** and recesses **434**, **438** have been moved close to the edges of the upper portion **418** and lower portion **422** while still maintaining a desired range of motion. This increases the 'footprint' of the contact points and maximizes the forces which tend to restore the joint to a neutral position when the joint is compressed.

By way of example, the following dimensions have been found to produce a suitable artificial joint for total disc replacement of cervical spine discs. The upper portion **418** and lower portion **422** are about 15.5 mm wide and about 11.9 mm long (front to back). The relatively flat base **442** of the upper portion **418** (extending between the projections **426**, **430**) is approximately 1.9 mm thick. On the upper portion **418**, the posterior projection **426** is approximately 11.2 mm in diameter, and has a center which is located along the lateral centerline, and positioned about 1.7 mm from the posterior edge of the upper portion. The posterior projection **426** is placed such that it extends approximately 3.6 mm from the base portion **442**, to a total combined thickness of about 5.5 mm.

The two anterior lateral projections **430** are approximately 6.9 mm in diameter, and have centers which are located about 7.2 mm in front of the center of the posterior projection **426** and laterally about 5.35 mm from the lateral centerline of the upper portion **418**. The anterior lateral projections **430** extend about 2.9 mm from the base portion **442**, to a total combined thickness of about 4.8 mm. Section lines **57** through **60** on FIG. **56** pass through the centers of the projections **426**, **430**.

FIGS. **67** and **68** illustrate the grinding/polishing tool paths used to form the lower section **422** as shown. FIG. **67** shows a top view of the tool paths overlaid on the lower portion **422** of the joint, and FIG. **68** shows a perspective view of the tool paths along with the resulting tool cuts and recesses. The posterior recess is made by sweeping a 15 mm diameter circular grinding/polishing tool through a horizontal arc **450** (so that the grinding diameter is perpendicular to the arc) where the arc has approximately a 1.8 mm radius and where the center **454** of the arc is centered laterally on the lower portion **422**, positioned 6.4 mm behind central reference point **446** (which is centered laterally and about 5.4 mm from the anterior edge or 6.6 mm from the posterior edge), and so that the center **454** is positioned about 4.9 mm above the upper surface of the lower portion **422**. The portion **458** of the posterior recess **434** which is inside of the lowest point ground by the tool is ground flat.

The two lateral anterior recesses **438** are made by sweeping a 10.8 mm diameter circular grinding/polishing tool across the tool path identified by path segments **462***a*, **466***a*, **470***a*, **474***a*, **474***b*, **470***b*, **466***b*, and **462***b*. Tool path segments **462***a*, **462***b* are straight lines of about 3.5 mm length. Tool path segments **466***a*, **466***b* are arcs having centers **478***a*, **478***b* and radii of about 0.9 mm. Tool path segments **470***a*, **470***b* are straight lines about 1.7 mm in length. Tool path segments **474***a*, **474***b* are arcs having a common center **482** and radii of about 6 mm. Center points **478***a*, **478***b* are located about 7 mm to each side of the lateral center line and are located about 4 mm forward of the reference point **446**, placing the points about 10.6 mm forward of the center point **454** and about 1.4 mm back from the anterior edge of the lower portion **422**. Center point **482** is located along the lateral center line and about 5.9 mm forwards of the reference point **446**, or about 0.3 mm forwards of the anterior edge of the lower portion **422**.

The various tool path segments **462** through **474** are connected into a continuous path as shown, and are located in a single plane. The plane in which the tool path segments are located is angled with respect to the lower segment so as to angle the forward portion **438***a* of the anterior recesses **438** as shown in FIG. **64**. As discussed previously, this causes the anterior end of the upper portion **418** to lower slightly relative to the anterior end of the lower portion **422** during flexion of the spine, replicating the natural motion of the spine. For the embodiment shown in FIGS. **54** through **68**, the plane is sloped downwardly about 17 degrees towards the anterior side of the joint. As such, the anterior most point **486** of the tool path (path segments **462** through **474**) is located about 0.9 mm above the upper surface of the lower portion **422**, and the path segments **470***a*, **470***b* are located about 3.5 mm above the upper surface of the lower portion.

It will be appreciated that the slope of the plane in which the tool path segments **462** through **474** are located may be zero if a simplified manufacturing process is desired. When the plane of the tool path segments **462** through **474** is sloped, it may typically be adjusted to match the specific disc which is being replaced, and may often be sloped at an angle of between about 7 and about 27 degrees less than horizontal. As discussed above, a middle cervical artificial disc will have a slope of about 17 degrees. The slope of the plane will typically be changed by adjusting the height of the anterior most point **486** of the tool path so as to keep the anterior recesses **438** at a similar average height and keep the height of the upper portion **418** relative to the lower portion **422** at a similar distance when the upper portion is in a neutral position.

The artificial spinal joints herein are beneficial in that they provide motion which closely replicates the artificial motion of the spine. An important aspect of this is providing a coupled motion, where translation or rotation of the upper portion relative to the lower portion necessarily produces a tilting of the upper portion relative to the lower portion. While some prior art artificial spine joints allow for translation, and allow for pivoting of the joint in a ball and socket like manner, there is no coupling of the translational movement and pivoting movement which approximates the natural motion of the spine. This results in a joint that provides an unnatural motion when implanted in a spine, and which adversely affects the spine as described herein. To the contrary, the inventive artificial spine joints provide a motion that closely replicates the natural spinal motion.

It is appreciated that the artificial discs disclosed herein will result in a high contact pressure between the projections and the recesses, as the curved surfaces of the projections contact the recesses at a very small contact area. Thus, the material used to create such a projection must withstand a very high pressure without deformation and without the wearing away, breaking, or other degradation of the material. Thus, a preferred embodiment of the present invention provides artificial discs which are formed from diamond, such as polycrystalline diamond compact (PDC). PDC is a sufficiently hard material to resist wear and deformation.

U.S. Publication No. 2003/0191533, assigned to Diamicron, Inc., discusses the manufacture of artificial joints using diamond, and is incorporated herein by reference. The publication makes known to one of skill in the art how to make artificial joints of artificial diamonds. With respect to the present invention, it is appreciated that it is more difficult to form a diamond artificial disc surface which is a complicated multi-projection or multi-recess surface. It is much simpler to form a simple regular surface such as a sphere or hemispherical receptacle.

A presently preferred method of manufacture of the artificial disc of the present invention uses electrical discharge machining (EDM) to form the joint surfaces. The artificial diamond compound may be pressed into roughly the desired shape. A sink EDM machine may then be fitted with an electrode which is the negative shape of the part being produced. The EDM and custom electrode are then used to burn away the diamond compound and refine the shape of the piece of the artificial joint. The resulting piece may then be polished to a finished surface. It is thus appreciated that the difficulty of forming the artificial disc out of diamond is a difficult process and may require some simplification of the artificial disc design.

Another currently preferred method of manufacture of the artificial joint of the present invention uses a circularly shaped grinding and polishing tool to sweep across the recesses and form the curved contact surfaces therein, and used a cup shaped grinding and polishing tool to form the spherical projections on the lower surfaces. This is particularly advantageous in forming the more geometrically shaped contact surfaces of the artificial joints of FIGS. **31** through **66**.

While PDC or other diamond materials are preferred, other biologically compatible metals and ceramics may also be used. Those familiar with the construction of artificial joints will be familiar with numerous such materials and the relative advantages and drawbacks of each.

There is thus disclosed an improved artificial vertebral disc. It will be appreciated that numerous changes may be made to the present invention without departing from the scope and spirit of the invention. The appended claims are intended to cover such modifications.

What is claimed is:

1. An artificial disc for forming an artificial joint in a spine comprising:

a first portion and a second portion which interact to form an artificial disc;

wherein the first portion comprises:

a first bone attachment surface located on a first side of the first portion for attaching the first portion to a vertebra;

a first articulation surface located on a second side of the first portion, the first articulation surface comprising three projections which extend from the first portion and which are spaced apart from each other;

wherein the second portion comprises;

a second bone attachment surface located on a first side of the second portion for attaching the second portion to a vertebra;

a second articulation surface located on a second side of the second portion,

wherein the three projections slide across the second articulation surface to allow movement of the artificial disc, and wherein the second articulation surface comprises a rigid generally convex portion disposed between the three projections.

2. The artificial disc of claim **1**, wherein the three projections comprise first and second projections which are spaced apart laterally and a third projection which is centered laterally and which is spaced apart in an anterior-posterior direction from the first and second projections.

3. The artificial disc of claim **1**, wherein the second articulation surface comprises three recesses which receive the three projections, and wherein a projection may slide to different locations within a recess to allow articulation of the artificial disc

4. The artificial disc of claim **1**, wherein the second articulation surface comprises a recess which is generally concave and which receives one of the three projections.

5. The artificial disc of claim **1**, wherein the second articulation surface comprises a recess which receives one of the three projections, and wherein the recess has a vertical cross section which is curved such that the recesses comprises a generally horizontal section disposed away from a center of the second articulation surface and a curved section connected thereto disposed adjacent the center of the second articulation surface.

6. The artificial disc of claim **1**, wherein the three projections are rigid and remain in contact with the second articulation surface during movement of the artificial joint.

7. The artificial disc of claim **1**, wherein the second articulation surface comprises generally concave recesses which receive the three projections and wherein the generally convex portion is disposed between the generally concave recesses.

8. The artificial disc of claim **1**, wherein the second articulation surface is curved such that a projection moves horizontally and vertically when the projection slides across the surface of the second articulation surface in a direction towards a center of the second articulation surface.

9. The artificial disc of claim **1**, wherein a projection moves generally horizontally when the projection slides across the surface of the second articulation surface in a direction away from a center of the second articulation surface.

10. An artificial disc for forming an artificial joint in a spine comprising:

an upper portion;

a first bone attachment surface located on the top of the upper portion for attaching the upper portion to a vertebra;

a first articulation surface located on the bottom of the upper portion, the first articulation surface comprising three projections which extend downwardly from the upper portion and which are spaced apart from each other;

a lower portion;

a second bone attachment surface located on the bottom of the lower portion for attaching the lower portion to a vertebra;

a second articulation surface located on the top of the lower portion, wherein the three projections slide across the second articulation surface in combined translation and rotation to allow movement of the artificial disc, and wherein the second articulation surface comprises three recesses which receive the three projections, and wherein a projection may slide to different locations within a recess to allow articulation of the artificial disc.

11. The artificial disc of claim **10**, wherein the three projections comprise one anterior projection and two posterior projections which are spaced apart laterally.

12. The artificial disc of claim **10**, wherein the three projections comprise one posterior projection and two anterior projections which are spaced apart laterally.

13. The articulation surface of claim **10**, wherein a recess has a vertical cross section which is curved such that the recesses comprises a generally horizontal section disposed away from a center of the lower portion and a upwardly curved section connected thereto disposed adjacent the center of the lower portion.

14. The artificial disc of claim **10**, wherein the three projections are rigid and remain in contact with the second articulation surface during movement of the artificial joint.

15. The artificial disc of claim **10**, wherein the second articulation surface is curved such that a projection moves horizontally and vertically when the projection slides across the surface of the second articulation surface in a direction towards a center of the lower portion.

16. The artificial disc of claim **15**, wherein said projection moves generally horizontally when said projection slides across the surface of the second articulation surface in a direction away from a center of the lower portion.

17. The artificial disc of claim **10**, wherein the three projections engage the second articulation surface to space a section of the upper portion between the three projections apart from the second articulation surface.

18. An artificial disc for forming an artificial joint in a spine comprising:

an upper portion;

a first bone attachment surface located on the top of the upper portion for attaching the upper portion to a vertebra;

a first articulation surface located on the bottom of the upper portion, the first articulation surface comprising three rigid projections which extend downwardly from the upper portion in a triangular arrangement;

a lower portion;

a second bone attachment surface located on the bottom of the lower portion for attaching the lower portion to a vertebra;

a second articulation surface located on the top of the lower portion, wherein the three projections slide across the second articulation surface while remaining in contact with the second articulation surface to allow movement of the artificial disc, and wherein the second articulation surface comprises three recesses associated with the three projections, and wherein a projection moves to different locations within a recess during movement of the artificial disc.

19. The artificial disc of claim **18**, wherein the upper portion moves in combined translational and rotational movement relative to the lower portion.

20. The artificial disc of claim **18**, wherein a recess has a vertical cross section which is curved such that the recesses comprises a generally horizontal section disposed away from a center of the lower portion and a upwardly curved section connected thereto disposed adjacent the center of the lower portion.

21. The artificial disc of claim **18**, wherein the recess is curved such that the projection moves upwardly when the projection slides in a direction towards a center of the lower portion and the projection moves generally horizontally when the projection slides away from a center of the lower portion relative to a neutral position of the artificial disc.

22. The artificial disc of claim **18**, wherein the three projections engage the second articulation surface to space a section of the upper portion between the three projections apart from the second articulation surface.

23. An artificial disc for forming an artificial joint in a spine comprising:

an upper portion;

a first bone attachment surface located on the top of the upper portion for attaching the upper portion to a vertebra;

a first articulation surface located on the bottom of the upper portion, the first articulation surface comprising three rigid projections which extend downwardly from the upper portion, said three rigid projections comprising first and second projections which are spaced apart laterally and a third projection which is centered laterally and which is spaced apart in an anterior-posterior direction from the first and second projections;

a lower portion;

a second bone attachment surface located on the bottom of the lower portion for attaching the lower portion to a vertebra;

a second articulation surface located on the top of the lower portion, wherein the three projections slide across the second articulation surface to allow movement of the artificial disc, and wherein the second articulation surface comprises three recesses which receive the three projections, and wherein a projection may slide to different locations within a recess to allow articulation of the artificial disc.

24. The artificial disc of claim **23**, wherein the three projections comprise one anterior projection and two posterior projections which are spaced apart laterally.

25. The artificial disc of claim **23**, wherein the three projections comprise one posterior projection and two anterior projections which are spaced apart laterally.

26. The articulation surface of claim **23**, wherein a recess has a vertical cross section which is curved such that the recesses comprises a generally horizontal section disposed away from a center of the lower portion and a upwardly curved section connected to the generally horizontal section and disposed adjacent the center of the lower portion.

27. The artificial disc of claim **23**, wherein the three projections remain in contact with the second articulation surface during movement of the artificial joint.

28. An artificial disc for forming an artificial joint in a spine comprising:

a first top portion and a second bottom portion which interact to form an artificial disc;

wherein the first portion comprises:

a first bone attachment surface located on a first side of the first portion for attaching the first portion to a vertebra;

a first articulation surface located on a second side of the first portion, the first articulation surface comprising three projections which extend downwardly from the first portion, said three projections comprising first and second projections which are spaced apart laterally and a third projection which is centered laterally and which is spaced apart in an anterior-posterior direction from the first and second projections;

wherein the second portion comprises;

a second bone attachment surface located on a first side of the second portion for attaching the second portion to a vertebra;

a second articulation surface located on a second side of the second portion,

wherein the three projections slide across the second articulation surface to allow movement of the artificial disc and wherein the three projections contact the second articulation surface at locations which extend away from a center of the second portion in a generally horizontal direction and which curve upwardly in a direction towards the center of the second portion.

29. The artificial disc of claim **28**, wherein the three projections are rigid and remain in contact with the second articulation surface.

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